THE Brattle GROUP

February 25, 2015

Ms. Marlene Dortch
Federal Communications Commission
445 12th Street, S.W.
Washington, D.C. 20554

Re: **Amendment of Part 15 of the Commission's Rules for Unlicensed Operations in the Television Bands, Repurposed 600 MHz Band, 600 MHz Guard Bands and Duplex Gap, and Channel 37; ET Docket No. 14-165, GN Docket No. 12-268**

Dear Ms. Dortch:

We hereby submit the attached report entitled "Unlicensed Operations in the 600 MHz Band: Fatally Flawed Twice Over" in the above-referenced dockets.

Sincerely,

Coleman Bazelon
Principal

cm
Enclosures

Unlicensed Operations in the 600 MHz Band: Fatally Flawed Twice Over

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February 25, 2015

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This report was prepared for Qualcomm. The authors are responsible for the results and for any errors. We want to acknowledge the many individuals who contributed to this report and to the underlying analysis, including members of The Brattle Group who conducted the peer review.

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Abstract

In its June 2014 Report and Order on the 600 MHz incentive auction, which will repurpose TV broadcast spectrum for mobile broadband service, the Federal Communications Commission (FCC) authorized the use of unlicensed devices in the post-auction guard bands, including the duplex gap ("guard bands"). This new directive extends a 2008 FCC order that authorized unlicensed use of vacant channels in the TV bands (TV white space) following the digital TV transition. Proponents assert that the propagation advantages of the 600 MHz band will allow unlicensed devices to operate more cheaply and effectively there than they can in the widely used unlicensed bands at 2.4 GHz and 5 GHz, thereby forestalling congestion in the existing unlicensed bands, powering a new wave of innovation, and providing mobile broadband coverage to underserved areas.

The FCC's proposed policy to allow unlicensed use of the 600 MHz guard bands is "fatally flawed twice over." First, the policy will be ineffective because the guard bands will fail to attract investment: their limited bandwidth makes the 600 MHz guard bands inferior to the unlicensed bands at 2.4 GHz and 5 GHz for Wi-Fi-type applications, and the necessarily limited transmit power precludes use of 600 MHz unlicensed devices altogether for long-range applications such as rural broadband. The best indication that the 600 MHz guard bands will not attract investment is the anemic market response to (unlicensed) TV white space, which faces similar handicaps.

Second, the FCC's proposed policy will be harmful because unlicensed use of the guard bands could cause interference to licensed mobile LTE services at 600 MHz, and the prospect of such interference will reduce the value of the 600 MHz spectrum, thus damaging the incentive auction. Our analysis of an LTE network in a band similar to 600 MHz shows that a 5 percent loss of capacity due to interference from unlicensed operations in the guard bands will lower the value of the affected spectrum by 9 percent; a 20 percent loss of capacity will lower its value by 43 percent; and a 35 percent loss of capacity will eliminate most (93 percent) of its value.

In addition to reducing the auction value of the 600 MHz broadcast spectrum, the prospect of interference will limit the quantity of broadcast spectrum that is repurposed to mobile broadband. For example, we estimate that, with a 10 percent level of interference (i.e., a 10 percent reduction in network capacity due to interference from unlicensed operations), the allocation-stage revenues will fall short of the required clearing costs for the FCC's five largest band plans, which means that the auction would fail to make available the amount of spectrum targeted in those band plans. Each 10 megahertz of broadcast spectrum that is not repurposed for mobile broadband represents at least $60 billion in lost consumer welfare. Thus, with only a 10 percent interference impact, the loss in consumer welfare could total more than $300 billion.

In addition to these direct effects, the prospect of interference from unlicensed operations could discourage bidding by new entrants, because they would have a much harder time working around its effects. This would further depress auction revenues and undermine key FCC policy goals.

Summary

In its June 2014 Report and Order on the 600 MHz incentive auction, which will repurpose TV broadcast spectrum for mobile broadband service, the Federal Communications Commission (FCC) authorized the use of unlicensed devices in the post-auction guard bands, including the duplex gap ("guard bands"). This new directive extends a 2008 order in which the FCC authorized unlicensed use of vacant channels in the TV bands (TV white space) following the digital TV transition. Our analysis shows that the FCC's proposed policy to allow unlicensed use of the 600 MHz guard bands is "fatally flawed twice over."

Fatal Flaw #1: Lack of Investment Will Doom the FCC's 600 MHz Guard Band Policy, Just As It Has Doomed the FCC's Policy on TV White Space

The FCC's proposal to allow unlicensed operations in the 600 MHz guard bands will be ineffective because it will fail to attract investment: their limited capacity makes the guard bands inferior to the existing unlicensed bands for short-range Wi-Fi-type applications, and the necessarily limited transmit power precludes their use altogether for rural broadband. The best predictor is the market's utter lack of interest in (unlicensed) TV white space, which faces similar handicaps.

"Wi-Fi on Tranquilizers"

For short-range data transfer applications such as Wi-Fi, cellular offload and machine-to-machine communications, unlicensed spectrum in the 600 MHz band will be substantially inferior to the existing unlicensed bands at 2.4 GHz and 5 GHz. Contrary to the promise of "Wi-Fi on steroids," unlicensed use of the 600 MHz guard bands will look more like "Wi-Fi on tranquilizers."

The big drawback to the 600 MHz guard bands for Wi-Fi-type applications is their limited capacity, due to the small amount of contiguous bandwidth available and the FCC's necessarily restrictive limit on transmit power:

- A 600 MHz unlicensed device will have to operate in a single six-megahertz channel (or smaller) and will likely be limited to 16 dBm EIRP (or 40 milliwatts) of transmit power. By comparison, Wi-Fi devices at 2.4 GHz and 5 GHz can operate using 20, 40, 80, or 160 megahertz of bandwidth, and they can transmit at a power of up to one watt.
- The bandwidth and transmit power limitations mean that unlicensed devices operating in the 600 MHz guard bands will have a data rate that is one-tenth to one-hundredth that of a Wi-Fi device operating at 2.4 GHz and 5 GHz. That handicap will trump any propagation advantages that the 600 MHz band may offer for most devices.
- Moreover, the 2.4 GHz and 5 GHz bands take better advantage of sophisticated antennas, including multiple-input/multiple-output (MIMO) technology. A

smartphone or camera designed to operate in the 600 MHz guard bands will not be able to take similar advantage of MIMO.

Unlicensed Systems in the Guard Bands Will Not Provide Rural Broadband Access

For long-range voice and data communications, unlicensed operations in the 600 MHz guard bands will have even less to offer. With a power limit of 40 milliwatts, unlicensed guard band devices will simply not be capable of providing rural broadband access and other long-range voice and data communication services.

Unlicensed TV White Space: Market Response Has Been Anemic

The best predictor of the market's likely response to unlicensed 600 MHz guard bands is the track record for unlicensed TV white space. Six years after the FCC approved the TV white space policy, and four years after it issued the final rules, neither equipment manufacturers nor users have shown interest in TV white space (see Section II for a discussion of the statistics cited below):

- The FCC has approved only nine products for operation in the TV white space, and none of the major manufacturers of Wi-Fi routers have fielded a product that can be used there. No major smartphone or tablet vendor sells a device that includes the capability to use TV white space.
- Users in this country have registered just over 500 individual devices with a TV white space database manager (device registrations are a proxy for sales).
- This is far from what proponents of TV white space predicted. In 2012, one device manufacturer projected that it would sell one million of its TV white space units in 2013 and 100 million in 2014. Based on device registrations in the TV white space database, that manufacturer (Adaptrum) has sold fewer than 100 TV white space units in this country to date.

This anemic market response likely reflects the low data rates that TV white space devices offer:

- The maximum data rates supported by TV white space devices range from 3.25-16 megabits per second (Mbps). That compares to maximum data rates of 600 Mbps to 1.7 gigabits per second for unlicensed devices that operate at 2.4 GHz and 5 GHz.
- Even the maximum data rate for TV white space devices (16 Mbps) falls below the FCC's new threshold for what constitutes a broadband (download) connection (25 Mbps). Moreover, many TV white space systems will not qualify for the FCC's Connect America Fund, which currently requires a data rate of at least 10 Mbps.

The anemic market response to TV white space is all the more striking compared to the robust investment that has taken place in other spectrum that the FCC has made available:

- The FCC auctioned 52 megahertz of licensed spectrum in the 700 MHz band in 2008 (the same year it approved unlicensed use of the TV white space), and within a few years, Verizon and AT&T began using the spectrum for which they paid $16 billion to build out national networks that provide LTE coverage.
- Unlicensed operations at 2.4 GHz and 5 GHz continue to grow at an explosive rate. The latest Wi-Fi standard (802.11ac), which takes advantage of "new" 5 GHz spectrum, allows for gigabit data rates. Device manufacturers have already marketed hundreds of products with the 802.11ac capability, including the Apple iPhone 6 (with sales of 10 million the first weekend it was available).

Fatal Flaw #2: Guard Band Operations Will Likely Interfere with Licensed Services, and the Prospect of Such Interference Could Severely Impact the Incentive Auction

In addition to being ineffective, the FCC's policy to allow unlicensed operations in the guard bands could be downright harmful because interference from those operations will compromise licensed mobile LTE services at 600 MHz.

Unlicensed Guard Band Operations Will Likely Cause Harmful Interference

In its recent Notice of Proposed Rulemaking, the FCC described the results of its technical analysis, which found that an unlicensed device using the 600 MHz guard bands would interfere with the operation of a licensed mobile device using LTE at 600 MHz if the two devices were less than 20 feet apart (see Section IV below for more detail):

- Although the FCC's finding will give potential bidders serious pause, it understates the real problem because key FCC assumptions about the loss of unlicensed signal strength are based on conditions that differ from those at hand.
- When we modify those assumptions to reflect the appropriate conditions, the estimated interference range is significantly larger (45 feet to 75 feet).

Harmful Interference from Unlicensed Operations Will Reduce LTE Network Capacity and the Corresponding Market Value of 600 MHz Spectrum

Interference from unlicensed operations in the 600 MHz guard bands will reduce the capacity of the LTE networks that use the affected 600 MHz spectrum, although the magnitude of the impact will depend on the rate at which 600 MHz unlicensed devices get deployed and used:

- For illustrative purposes, we estimate that interference could reduce capacity by an amount ranging from 5 percent to 35 percent. We use 5 percent as the low-end estimate because even a limited deployment of 600 MHz unlicensed devices will have some adverse impact. We use 35 percent as the high-end estimate because, if the reduction in capacity exceeds 35 percent, the band will lose all value for deployment of an LTE network.

A loss of capacity due to interference from unlicensed operations will in turn reduce the market value of the affected bands of 600 MHz spectrum, because the carrier will need to compensate by adding cell sites that use unaffected bands elsewhere in its network, and that cost will reduce the carrier's net cash flow.

- Based on our analysis of an LTE network in a band similar to 600 MHz, we find that a 5 percent loss of capacity will lower the value of the affected spectrum by at least 9 percent; a 20 percent loss of capacity will lower its value by at least 43 percent; and a 35 percent loss of capacity will eliminate most (93 percent) of its value.

In sum, spectrum that is subject to interference has a lower market value than spectrum that is not subject to interference, and even a relatively small level of interference can cause a sizable drop in the market value of the affected spectrum.

A Reduction in the Value of 600 MHz Spectrum Could Severely Damage the Incentive Auction

The prospect of interference from unlicensed operations, by reducing the market value of the 600 MHz spectrum, could severely damage the incentive auction. The impacts include a reduction in auction revenues, a decrease in the amount of spectrum repurposed for mobile broadband, and a corresponding loss of consumer welfare totaling hundreds of billions of dollars.

As a baseline, we illustrate how the incentive auction could play out in the absence of any risk of interference, drawing on plausible estimates of spectrum value and broadcaster compensation costs from industry experts:

- Positing a market value for the 600 MHz spectrum of $2.00/MHz-pop, we show that the forward auction would generate from $12 billion to $75 billion, depending on which of the FCC's 11 band-plan scenarios one uses.
- Total clearing costs (broadcaster compensation costs plus the cost to relocate broadcasters and cover FCC expenses) would range from $6 billion to $63 billion, depending on the band plan.

The outcome of the incentive auction changes dramatically when we take into account the risk of interference from unlicensed operations (where the level of interference is defined as the percent of lost network capacity). Two features of the auction magnify the impact of this risk.

First, as the FCC now envisions the auction, at the allocation stage, bidders will be unable to distinguish between those blocks that are subject to interference from unlicensed operations and those that are not. Thus, rational bidders will assume that all blocks are subject to interference. We quantify the lost auction revenues as follows:

- We estimate that the allocation-stage revenues will decrease by an amount ranging from 9 percent (for a 5 percent level of interference) to 93 percent (for a 35 percent level of interference).

- Using for purposes of illustration the FCC's 84-megahertz band plan (84 megahertz of broadcast spectrum cleared and 70 megahertz repurposed for mobile broadband), with a 5 percent level of interference, total allocation-stage revenues will be reduced by $4 billion, to about $40.3 billion. At the 35 percent level, allocation-stage revenues for this plan will be reduced by about $41.2 billion, to $3.0 billion.

Second, even though some of the revenue lost at the allocation stage will be recovered in the assignment round (when bidders will be able to identify individual blocks), the amount of TV spectrum cleared depends solely on the revenue generated in the allocation stage, which must cover total clearing costs. (If allocation-stage revenues do not cover clearing costs, the FCC will ratchet down to the next largest band plan.) Thus, the prospect of interference, by reducing allocation-stage revenues, will limit how much spectrum even makes it to the assignment round:

- At the 10 percent level of interference, allocation-stage revenues will fall short of required clearing costs for the FCC's five largest band plans. Under that interference scenario, the largest feasible plan would be the illustrative band plan, which would clear 84 megahertz and repurpose 70 megahertz for mobile broadband. This is 50 megahertz less than would be repurposed under the FCC's largest band plan (144 megahertz cleared, 120 megahertz repurposed), and some of it would be subject to interference to boot.
- At the 15 percent level of interference, allocation-stage revenues will fall short of required clearing costs for seven of the 11 band plans. Only the three smallest band plans and the illustrative band plan would cover their clearing costs (the illustrative plan can theoretically "tolerate" a greater percentage of interference than some of the smaller plans because it has less spectrum devoted to guard bands). Of the three smallest band plans, the largest one would clear 60 megahertz of broadcast spectrum and repurpose 40 of it—a third of what the FCC's largest plan would repurpose.
- At the 20 percent level of interference, allocation-stage revenues will fall short of clearing costs for fully nine of the 11 FCC band plans. Only the two smallest band plans are likely to succeed: one would clear 48 megahertz, of which 30 would be repurposed; the other would clear 42 megahertz and repurpose 20 megahertz. Because some portion of the repurposed spectrum (20 or 30 megahertz, depending on the plan) would be subject to interference, the amount of "clear" 600 MHz spectrum repurposed for mobile broadband use would be even less.

The auction would be completely unsuccessful only if the allocation-stage revenues from the smallest band plan were to fall short of its clearing costs. Even short of that scenario, however, if the interference from unlicensed operations were to cause a reduction in the amount of broadcast spectrum that got repurposed for mobile broadband, it would impose an enormous social cost.

- We estimate that every 10 megahertz of broadcast spectrum that is not repurposed for mobile broadband represents at least a $60 billion loss in consumer welfare.
- Thus, with only a 10 percent level of interference, the best possible outcome (70 megahertz repurposed) would represent at least a $300 billion loss in consumer welfare relative to the FCC's largest band plan (120 megahertz repurposed).

In addition to these direct effects, the prospect of interference from unlicensed operations could discourage bidding by new entrants, who—lacking substitutable spectrum that is not subject to interference—would have a much harder time working around the effects of the interference. This would further depress auction receipts and undermine key FCC policy goals.

I. Introduction

In its June 2014 Report and Order on the 600 MHz incentive auction, which will repurpose TV broadcast spectrum for mobile broadband service, the Federal Communications Commission (FCC) authorized the use of unlicensed devices (including wireless microphones) in the post-auction guard bands, including the duplex gap (referred to collectively as "600 MHz guard bands" or "guard bands").[1] This new directive extends a 2008 order in which the FCC authorized the unlicensed use of vacant channels in the TV bands (TV white space) following the digital TV transition.[2]

Proponents of these two directives assert that the propagation advantages of the lower bands (the TV bands and the reconstituted 600 MHz band) will allow unlicensed devices to operate more efficiently and effectively there than they can in the 2.4 GHz and 5 GHz bands, where most unlicensed activity occurs now. Such operations, they argue, will help forestall congestion in the existing unlicensed bands and, at the same time, stimulate a new wave of innovation and provide mobile broadband coverage to unserved and underserved areas.

In reports filed in 2007 and 2008 as part of the FCC's TV white space proceeding, the authors of this report argued that, contrary to claims that it would bring us "Wi-Fi on steroids," the TV white space spectrum was in fact poorly suited for most unlicensed applications. We went so far as to say that allowing unlicensed access to the TV white space would be "wasteful and harmful."[3]

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1 *Expanding the Economic and Innovation Opportunities of Spectrum Through Incentive Auctions*, GN Docket No. 12-268, Report and Order, FCC 14-50 (rel. June 2, 2014) ("600 MHz Report and Order"). The FCC has not specified the exact frequencies that will make up the guard bands, pending the determination through the auction process of the amount of broadcast spectrum that will be repurposed and the Commission's choice of the corresponding band plan.

2 *Unlicensed Operation in the TV Broadcast Bands* and *Additional Spectrum for Unlicensed Devices Below 900 MHz and in the 3 GHz Band*, ET Docket No. 04-186 and ET-Docket No. 02-380, Second Report and Order and Memorandum Opinion and Order, FCC 08-260 (rel. November 14, 2008).

3 Comments of Charles L. Jackson and Dorothy Robyn, *Unlicensed Operation in the TV Broadcast Bands* and *Additional Spectrum for Unlicensed Devices Below 900 MHz and in the 3 GHz Band*, ET Docket No. 04-186 and ET Docket No. 02-380 (January 31, 2007); Reply Comments of Charles L. Jackson and Dorothy Robyn, *Unlicensed Operation in the TV Broadcast Bands* and *Additional Spectrum for Unlicensed Devices Below 900 MHz and in the 3 GHz Band*, ET Docket No. 04-186 and ET Docket No. 02-380 (March 2, 2007); Comments of Charles L. Jackson, Dorothy Robyn and

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We said that it would be wasteful because the propagation advantages of the TV band would be more than offset by fundamental impediments to the use of unlicensed devices there—principally, the lack of capacity for short-range data transfer such as Wi-Fi-type connectivity, and the stringent power restrictions on, and lack of interference protection for, long-range voice and data communications such as rural broadband service. We predicted that those impediments, together with the availability of measurably superior options (the 2.4 GHz and 5 GHz unlicensed bands for short-range data transfer and licensed spectrum for long-range communications), would severely limit investment in unlicensed devices for the TV white space.

In addition to being wasteful, we said that allowing unlicensed access to the TV white space would be harmful because of the significant opportunity cost it would impose. We argued that it was feasible to auction off the TV white space, and we showed how, in a licensed regime, the combination of reduced interference protection and licensee incentive to negotiate boundaries would make it possible to utilize fully twice as much of the collective white space as in an unlicensed regime. We estimated that an auction of rights to the TV white space would generate from $9.4 billion to $24.4 billion in revenue, depending on the interference-protection rules and the number of channels included.

Our criticism of the TV white space policy was by no means a critique of all FCC policies that authorize unlicensed operations. To the contrary, the unlicensed operations at 2.4 GHz and 5 GHz allow for the use of resources that would otherwise be idle, and the resulting ecosystem of devices and innovation has been a huge boon to consumers. The 900 MHz unlicensed band has been similarly successful. By contrast, the TV white space would not have "otherwise been idle"—it could have been auctioned off—and there was little reason in 2007 to think that unlicensed access to the TV white space would bring meaningful benefits to consumers. (The evidence to date, which we review in Section II, only confirms that view.)

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Coleman Bazelon, *Service Rules for the 698-746, 747-762 and 777-792 MHz Bands and Implementing a Nationwide, Broadband, Interoperable Public Safety Network in the 700 MHz Band*, WT Docket No. 06-150 and PS Docket No. 06-229 (June 20, 2008); Comments of Charles L. Jackson, Dorothy Robyn and Coleman Bazelon, "Unlicensed Use of the TV White Space: Wasteful and Harmful," Ex Parte Comment, *Unlicensed Operation in the TV Broadcast Bands,* ET Docket 04-186, (August 20, 2008); and Comments of Charles L. Jackson, "Unlicensed TV White Space Wireless Cannot Provide Substantial Rural Broadband Access," Ex Parte Comment, *Unlicensed Operation in the TV Broadcast Bands,* ET Docket No. 04-186 (October 22, 2008).

The concerns that we raised in 2007 and 2008 about the FCC's policy on TV white space are directly relevant to the debate over allowing unlicensed operations in the 600 MHz guard bands. First, the factors that make the TV white space unsuitable for most unlicensed applications apply as well to the 600 MHz guard bands. In fact, the 600 MHz guard bands will be even more limited than the TV white space in terms of capacity. Moreover, the FCC's proposed power limit for 600 MHz guard band devices is lower even than the one for TV white space devices (and appropriately so), which will eliminate any potential to use guard band devices for long-range voice and data communications and reduce whatever small niche market for short-range data transfer that TV white space devices may enjoy.

Second, as with the TV white space, unlicensed use of the 600 MHz guard bands will impose a significant opportunity cost. In contrast to the TV white space, which could have been auctioned off for licensed use, the 600 MHz guard bands must function as a buffer to prevent interference between licensed bands; thus, there is no foregone auction revenue. However, unlicensed use of the 600 MHz guard bands nevertheless will impose a cost because, contrary to the belief of some parties, it will impair licensed LTE operations in nearby bands. Although the degree of interference is unclear, the prospect of interference could cause substantial economic harm and severely damage the incentive auction.

In this report, we analyze these concerns in more detail. In the first half of the report, we look at why the FCC's policy to allow unlicensed operations in the 600 MHz guard bands is likely to be ineffective. Specifically, in Section II, we look at how the market has responded to the FCC's 2008 policy which allocated the TV white space for unlicensed use. We contrast that tepid response to the rapid build-out of licensed systems in the 700 MHz band and to the explosive growth of unlicensed devices developed for use in the 2.4 GHz and 5 GHz bands. In Section III, we look at the factors that have impeded the performance of and investment in TV white space devices, and we analyze whether 600 MHz guard band devices will face the same (or other) impediments.

In the second half of the report, we measure the opportunity cost of allowing unlicensed use of the 600 MHz guard bands. Section IV contains our technical analysis of the potential for unlicensed operations in the 600 MHz guard bands to adversely impact licensed mobile LTE services at 600 MHz. In Section V, we quantify the fraction of capacity, or productivity, that a licensed LTE network at 600 MHz would lose if LTE handsets were subject to harmful interference, and we analyze how alternative levels of capacity reduction would affect the value of the affected spectrum. In Section VI, we trace the way in which the prospect of interference, through its adverse impact on the value of spectrum in the 600 MHz band, would damage the auction. The structure of the auction is key to the analysis because the prospect of interference will take its major toll on the allocation stage, thus limiting the amount of spectrum that even makes it to the assignment round to be repurposed for mobile broadband.

II. Unlicensed Use of the TV White Space

The claims made for unlicensed access to the 600 MHz guard bands (which we discuss further in Section III) are identical to the ones made for the TV white space prior to the FCC's 2008 order. In 2007, Dell Chief Executive Officer Michael Dell described the "multi-billion market, just waiting to explode, if [unlicensed] next-generation home and office wireless networking devices are enabled in the white spaces."[4] The New America Foundation pointed to the "enormous opportunity for local communities, governments and service providers to transform unused TV channels into rocket-fuel for wireless broadband."[5] And Google co-founder Larry Page famously said that unlicensed access to the TV white space would bring about "Wi-Fi on steroids."[6]

The ultimate test of the FCC's policy on unlicensed use of the TV white space is whether the market (principally device manufacturers and users) respond to it as a commercial opportunity. Moreover, given the strong similarities between TV white space and 600 MHz guard bands (both the spectrum itself and the FCC policy to promote unlicensed use of it), the market's response to the former should be an excellent predictor of the commercial fate of the latter.

A. Market Response

The market's response to the TV white space opportunity to date has been, to be kind, anemic. Most significant is the lack of interest from device manufacturers. Although the FCC authorized unlicensed use of the TV white space in 2008 and issued final rules in 2010, the FCC has approved only nine products for operation in the TV white space (and all are fixed devices).[7]

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4 Dell made the statement at a meeting with FCC Chairman Kevin Martin and others at the Consumer Electronics Show in Las Vegas, NV, in 2007; it was cited in Scott Blake Harris, Ex Parte Letter, *Unlicensed Operation in the TV Broadcast Bands* and *Bi-Directional Digital Cable Compatibility and Related Issues*, ET Docket No. 04-186 and CS Docket No. 97-80 (January 12, 2007).

5 Benjamin Lennett, "Rural Broadband and the TV White Space: How Unlicensed Access to Vacant Television Channels Can Bring Affordable Wireless Broadband to Rural America," Wireless Future Program, New America Foundation, Issue Brief #22, June 2008, p. 1.

6 Amy Schatz, "FCC to Decide in Battle for TV Spectrum," *Wall Street Journal,* August 18, 2008.

7 See "Equipment Authorization Search," Federal Communications Commission, accessed November 21, 2014, under Equipment Class: WGF-White Space Device with Geo-location-Fixed; available at https://apps.fcc.gov/oetcf/eas/reports/GenericSearch.cfm?calledFromFrame=N. The first white space device to get FCC approval, in late 2011, was a software-defined radio developed by Koos Technical

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Especially telling is that no major manufacturer of Wi-Fi routers (e.g., Cisco, Linksys and Netgear) has fielded a product for the TV white space. Nor does any major manufacturer of smartphones or tablets produce a product with the capability to use TV white space. By contrast, the iPhone 6 includes the capability to use the cutting-edge Wi-Fi standard, 802.11ac, which received final approval from the Institute of Electrical and Electronics Engineers (IEEE) and the American National Standards Institute (ANSI) only late in 2013.

The response from the user community to the TV white space has been equally languid. Although sales figures are not publicly available, device registrations serve as a proxy for U.S. sales. (Users must register their device with the appropriate white space database manager and, once registered, a device appears in each of the privately managed databases.) Just over 570 individual devices have been registered in this country, and two of the nine FCC-approved products appear to account for half of them.[8]

This poor user response is far from what proponents of TV white space predicted a few years ago. In 2012, Adaptrum projected that it would sell one million of its TV white space units in 2013 and one hundred million units in 2014.[9] Adaptrum's actual sales in this country to date appear to total less than 100 units.[10]

The response has been stronger from companies that want to manage the databases designed to keep track of whether a white space channel is available for use. The FCC has approved four companies to perform this function, including Google and Spectrum Bridge, and several other applications are pending. Each FCC-approved device has a corresponding database manager. For example, Spectrum Bridge manages the database for the KTS White Space Radio.

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Services (KTS). Adaptrum Inc., Carlson Wireless Technologies, Meld Technology, and two Canadian firms have also had devices approved for use in the TV white space.

8 As of February 4, 2015, 572 devices were registered on the Google Spectrum Database. See "Registered Fixed TV-band White Space Devices," Google Spectrum Database, accessed February 4, 2015; available at https://www.google.com/get/spectrumdatabase/data/.

9 See Adaptrum, PowerPoint Presentation, at slide 14; available at http://noc.ucsc.edu/docs/White-space/CENIC-GigU_presentations_Oct_2012/Adaptrum_TVWS_Info_Cenic1_101612.pdf.

10 As of February 4, 2015, only 86 Adaptrum fixed devices were registered on the Google Spectrum Database. See "Registered Fixed TV-band White Space Devices," Google Spectrum Database, accessed February 4, 2015; available at https://www.google.com/get/spectrumdatabase/data/. See also footnote 7.

B. TECHNOLOGY PERFORMANCE

This anemic market response likely reflects the low data rates that TV white space devices provide. For example, Adaptrum's website says that its Whitespace System operates at speeds of up to 16 megabits per second (Mbps) per channel.[11] For the two FCC-approved devices that KTS is marketing, the top speed is 3.25 Mbps.[12]

These speeds are a fraction of the 80 Mbps data rates that the White Spaces Coalition promised in 2007.[13] More important, they are a tiny fraction of what users can achieve in the 2.4 GHz and 5 GHz unlicensed bands. Qualcomm and Broadcom both make chips for unlicensed devices that operate at 2.4 GHz and 5 GHz. According to their websites, Qualcomm's four-stream VIVE and Broadcom's BCM4360 products, which operate in channels as wide as 160 megahertz, support data rates of up to 1.7 gigabits per second (Gbps) and 1.3 Gbps, respectively—roughly 100 times the speed of Adaptrum's Whitespace System.[14]

To use another index, the maximum data rate for white space devices (16 Mbps) falls below the FCC's new definition of what constitutes a broadband Internet download connection (25 Mbps). Thus, service providers relying on white space devices will not be able to claim that they provide broadband service. Moreover, in many cases, they may not even qualify for support from the Connect America Fund (CAF), the FCC's program to subsidize mobile phone and broadband service in rural and other underserved areas. CAF currently requires qualifying systems to have a download data rate of at least 10 Mbps.

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11 See "Adaptrum ACRS 1.0 TV Whitespace System Specifications," Adaptrum Inc., accessed November 24, 2014; available at http://www.adaptrum.com/docs/adaptrum_datasheet_acrs10.pdf.

12 See Agility White Space Radio product page, KTS Wireless, accessed November 24, 2014; available at http://www.ktswireless.com/agility-white-space-radio-awr/.

13 Eric Bangeman, "The White Spaces Coalition's Plans for Fast Wireless Broadband," *Ars Technica,* April 18, 2007; available at http://arstechnica.com/gadgets/2007/04/white-space/. See also, Nick Valéry, "White-Space Puts Wi-Fi on Steroids," *The Economist,* Nov. 17, 2011; available at http://www.economist.com/node/21536999.

14 For Qualcomm's VIVE product page see "Qualcomm MU | EFX: Multiply Your Wow," Qualcomm Atheros, Inc., accessed November 24, 2014; available at http://www.qca.qualcomm.com/products/qualcomm-vive/. For Broadcom's BCM4360 product page see "5G WiFi 3-Stream 802.11ac Gigabit Transceiver," Broadcom Corporation, accessed November 24, 2014; available at http://www.broadcom.com/products/Wireless-LAN/802.11-Wireless-LAN-Solutions/BCM4360.

C. Applications

Given how limited the deployment of TV white space devices has been, it is difficult to infer much about how the devices are being used. Several technology demonstrations are underway that appear to have some level of outside sponsorship. For example, the first demonstration of white space devices occurred in early 2012 in Wilmington, North Carolina, the community in which the FCC pilot-tested its subsequent (2009) rollout of the nationwide digital TV transition. Wilmington is using a KTS Wireless device as a last-mile transmitter to provide internet access in public parks and to remotely monitor some of the city's water and lighting infrastructure.[15]

Another early adopter was West Virginia University, which is located in a mountainous area. Adaptrum devices provide backhaul from Wi-Fi access points located at five stations in the campus's light rail system. Because there are relatively few TV stations nearby, Adaptrum can use 12 channels of TV white space and offer a total data rate that is quite high (12 channels × 14 Mbps/channel).[16] However, it requires 12 pairs of radios (one per channel) to achieve this rate. By contrast, Wi-Fi at 2.4 GHz and 5 GHz achieves higher data rates with just one pair of radios, although the Wi-Fi signal typically has slightly less range.[17]

D. Regulatory Uncertainty or Market Disinterest?

Those who support the FCC's policy on TV white space attribute the slow market response to regulatory uncertainty, and there may be something to that. Although the FCC first acted to allow fixed unlicensed devices to operate on vacant TV channels as far back as 2006 in a proceeding that had begun in 2004, the Commission did not adopt final technical rules until 2008, and it took two more years for the FCC to rule on multiple petitions for reconsideration of

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15 See Elizabeth Woyke, "World's First Commercial White Spaces Network Launching Today in North Carolina," *Forbes,* Jan. 26, 2012; available at http://www.forbes.com/sites/elizabethwoyke/2012/01/26/worlds-first-commercial-white-spaces-network-launching-today-in-north-carolina/. See also, Lyndsey Gilpin, "White Space Broadband: 10 Communities Doing Big Projects," *TechRepublic,* March 19, 2014; available at http://www.techrepublic.com/article/white-space-broadband-10-communities-doing-big-projects/.

16 John Cox, "Better than TV! White Spaces Bring Wireless Bonanza to West Virginia," *NetworkWorld,* Jan. 22, 2014; available at http://www.networkworld.com/article/2173545/wireless/better-than-tv--white-spaces-bring-wireless-bonanza-to-west-virginia.html.

17 The issue of how signal range varies from one frequency to another is complex, and it is made more so here by the fact that the FCC's rules allow higher radiated powers at 2.4 GHz and 5 GHz than in the TV white space.

the 2008 order. Thus, equipment developers did not know the final "rules of the road" for TV white space until 2010. Moreover, the prospect of the incentive auction, which the FCC proposed in 2010 and Congress authorized in 2012, introduced additional uncertainty: following a successful auction, the FCC will repack the remaining broadcast stations, thus changing the number and location of TV white spaces.[18]

Although one cannot rule out regulatory uncertainty as a factor, in our view, the anemic market response to the TV white space opportunity is due largely to fundamentals. The slow data rates are a showstopper for many applications. When one adds in the cost and complexity of filters needed to protect television reception, TV white space devices are a decidedly inferior option to devices that operate at 2.4 GHz and 5 GHz for most short-range, data networking applications.[19]

The New America Foundation, which predicted that TV white space would serve as "rocket fuel for wireless broadband," appears to have redefined success. Michael Calabrese, the head of New America's wireless program, told the Internet Society last year that TV white space was "not for capacity, it's for coverage."[20]

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18 See "Incentive Auctions: Unleashing Spectrum to Meet America's Demand for Mobile Broadband," Federal Communications Commission, accessed November 24, 2014; available at http://www.fcc.gov/incentiveauctions.

19 Consider the comments of Preston F. Marshall, a prominent spectrum engineer who has worked for the Department of Defense's Defense Advanced Research Projects Agency (DARPA) and who now serves as Google's Principal Wireless Architect. Marshall told a gathering of the Internet Society in 2013 that, with the wireless sector having achieved national coverage, the challenge was to get capacity. He stressed that the shortage was not in spectrum, but rather in infrastructure, including Wi-Fi access points and macrocell sectors. Marshall said, "People [have] thought of low frequencies as being beachfront [but] I think of low frequencies as being the last thing I want!" He said it was the higher frequencies that allowed for capacity-creating infrastructure, because the signals were short range ("I want to have a lot of these grouped next to each other") and low power. Preston F. Marshall, "Wireless 2020: Spectrum Crisis or Broadband Abundance," Internet Society, Washington, DC, Nov. 1, 2013; available at https://www.youtube.com/watch?v=LxOlqLAvClE.

20 Michael Calabrese, "Wireless 2020: Spectrum Crisis or Broadband Abundance," Internet Society, Washington, DC, Nov. 1, 2013; available at https://www.youtube.com/watch?v=LxOlqLAvClE. Calabrese's statement reflects a scaled-back projection of what unlicensed TV white space will be able to accomplish. For example, in 2007, Calabrese said that "white space devices will transform every aspect of civil society." See Michael Calabrese and Sascha Meinrath, "Michael Calabrese in eWeek on White Space Devices," New America Foundation, December 13, 2007; available at http://oti.newamerica.net/node/20083.

Even that goal seems farfetched, however. Given the challenges to its use for long-range applications (4 watt power limit and the risk of interference from short-range devices), unlicensed TV white space is unlikely to expand rural broadband coverage in any meaningful way. Granted, some communities, campuses and farms may get some services that they did not have before. But those benefits will be limited and they will be achieved at a very high (social) cost—namely, the billions of dollars in auction revenues and consumer benefits that licensed use of the TV white space would have generated.

To its credit, in a recent Notice of Proposed Rulemaking ("600 MHz Unlicensed NPRM"), the FCC proposes changes to some of the rules governing operation of unlicensed devices in the TV white space.[21] Although these proposals would not overcome all of the impediments that the TV white space faces, we applaud the Commission's effort to make that spectrum marginally more attractive to unlicensed device manufacturers and users.[22]

E. Robust Investment in Other Bands of Spectrum

The anemic market response to the TV white space is all the more striking when one compares it to the robust investment that has taken place in systems that use other parts of the radio spectrum that the FCC has made available.

1. Rapid Buildout of 700 MHz

In 2008, the same year that the FCC authorized the use of unlicensed devices in the TV white space, the Commission auctioned 52 megahertz of broadcast spectrum in the 700 MHz band for

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[21] *In the Matter of Amendment of Part 15 of the Commission's Rules for Unlicensed Operations in the Television Bands, Repurposed 600 MHz Band, 600 MHz Guard Bands and Duplex Gap, and Channel 37* and *Amendment of Part 74 of the Commission's Rules for Low Power Auxiliary Stations in the Repurposed 600 MHz Band and 600 MHz Duplex Gap* and *Expanding the Economic and Innovation Opportunities of Spectrum Through Incentive Auctions*, ET Docket No. 14-165 and GN Docket No. 12-268, Notice of Proposed Rulemaking, FCC 14-144 (rel. September 30, 2014).

[22] Based on a cursory review of the FCC's proposed changes, we identified several of them that are likely to provide benefits to consumers with few if any offsetting costs. The most significant proposals would adopt separation distances that reflect actual transmitted power; raise the permitted antenna height in rural areas and allow for use of higher-gain antennas; and explicitly allow white space devices to operate on adjacent white space channels as if they were a single bonded channel. Two other promising proposals would permit white space devices to operate on TV Channels 3 and 4; and permit white space devices to operate on TV Channels 14-20 (subject to protection of land mobile operations). In omitting other changes proposed by the FCC from this list, we do not mean to imply that they might not also provide benefits to consumers.

mobile broadband uses.[23] The FCC cleared broadcasters from the 700 MHz band in 2009, and the two largest U.S. wireless carriers, having paid $16 billion to acquire the spectrum, moved quickly to build out their national networks.[24] Verizon now uses its Upper 700 MHz C Block spectrum to operate 41,500 cell sites in more than 500 markets, and those cell sites reach 97 percent of the U.S. population.[25] AT&T used the spectrum it acquired in the auction to build out its network of cell sites, and AT&T's 700 MHz network now reaches roughly 92 percent of the U.S. population.[26]

The 2008 sale of 700 MHz spectrum has been key to the successful deployment and growth of LTE, the fourth generation cellular standard and a technology in which U.S. companies are reasonably dominant. The U.S. leads the world in LTE deployments and a majority of commercial 700 MHz band deployments are LTE;[27] more than 150 million LTE devices were

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[23] Auction 73, which offered 62 megahertz of spectrum in the 700 MHz band, was held from January to March 2008. It produced winning bids—i.e., bids that exceeded FCC clearing costs—for the A, B, C and E Blocks, for a total of 52 megahertz of spectrum. The 10 megahertz in the D block did not receive a bid sufficient to cover FCC clearing costs and thus was not licensed at the time (it was ultimately licensed to the public safety community). See "Auction 73: 700 MHz Band," Federal Communications Commission, accessed November 24, 2014; available at http://wireless.fcc.gov/auctions/default.htm?job=auction_summary&id=73.

[24] Verizon bid $9.4 billion and AT&T bid $6.6 billion for spectrum. See Bryan Gardiner, "In Spectrum Auction, Winners are AT&T, Verizon, and Openness," *Wired*, March 20, 2008; available at http://www.wired.com/2008/03/fcc-releases-70/.

[25] According to Citi Research Equities, Verizon's Upper 700 MHz C Block had 41,500 LTE cell sites at the end of the third quarter in 2013. See Michael Rollins, Jason Bazinet and Kevin Toomey, "Third Pipe: Next Gen Wireless," Citi Research Equities, June 5, 2014, p. 17. In addition, in its 2013 10-K, Verizon Wireless reports that its Upper 700 MHz C Block spectrum, which the carrier uses to operate its 4G LTE network, covers 97 percent of the U.S. population, or roughly 305 million people. See also Verizon Communications Inc. Form 10-K for the year ending December 31, 2013, p. 2.

[26] The FCC's rules imposed build-out requirements on the 700 MHz licensees. However, the networks that the licensees built far exceeded the FCC requirements. In its Annual Report, AT&T reports that 4G LTE covers 280 million (roughly 92 percent) of the U.S. population, or roughly 305 million people. See AT&T Inc. 2013 Annual Report, p. 5.

[27] The U.S. accounts for 5 percent of global wireless subscribers but 47 percent of LTE subscribers. See CTIA, "Wireless Quick Facts" (World Leader), accessed February 4, 2015; available at http://www.ctia.org/your-wireless-life/how-wireless-works/wireless-quick-facts. For example, AT&T, Verizon and T-Mobile all use 700 MHz for their LTE Networks. See Phil Goldstein, "AT&T to Use Lower 700 MHz D and E Block Spectrum for LTE Broadcast," FierceWireless, September 24, 2013, accessed February 9, 2015; available at http://www.fiercewireless.com/story/att-use-lower-700-mhz-d-and-e-block-spectrum-lte-broadcast/2013-09-24. See also Sam Churchill, "Verizon 700 MHz LTE: We're Done!," DailyWireless, June 27, 2013, accessed February 9, 2015; available at

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deployed in this country in 2014 alone.[28] U.S. wireless carriers are also investing more in spectrum deployment than ever before—much of that related to LTE. In 2013, U.S. wireless carriers invested $33 billion in capital expenditures, which is four times more per subscriber than the amount that non-U.S. wireless carriers invested outside of the United States.[29]

2. Unlicensed Operations at 2.4 GHz and 5 GHz

The continued explosive growth in unlicensed operations in the 2.4 GHz and 5 GHz bands is an equally sharp contrast to the market's tepid response to TV white space. Wi-Fi, the most familiar unlicensed radio system, operates in three unlicensed radio bands—2.4 GHz, 5 GHz and (more recently) 60 GHz. In recent years, Congress and the FCC have worked both to expand the unlicensed band at 5 GHz and to update the rules to facilitate greater use. Cisco characterized as "historic" the FCC's March 2014 decision to open up another 100 megahertz of the 5 GHz band for use by outdoor access points and to reopen a portion of the band that had been closed to Wi-Fi use.[30] In an ongoing proceeding, the FCC is proposing to expand still further the portions of the 5 GHz band that are available for unlicensed use. A senior official with Comcast Corporation told Congress last year that "the future of Wi-Fi is in the 5 GHz band."[31]

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http://www.dailywireless.org/2013/06/27/verizon-700-mhz-lte-were-done/; and also Neal Gompa, "T-Mobile Buys Verizon's Lower 700MHz Spectrum to Enable Broad-Coverage 200 Mbps LTE," ExtremeTech, January 8, 2014, accessed February 9, 2015; available at http://www.extremetech.com/computing/174299-t-mobile-buys-verizons-lower-700mhz-spectrum-to-enable-broad-coverage-200mbps-lte.

28 Robert Pepper and Doug Webster, "Cisco Visual Networking Index (VNI) Forecast: Mobile Data Traffic Update, 2014-2019," PowerPoint Presentation, February 3, 2015.

29 CTIA, "Wireless Quick Facts" (Investment), accessed February 4, 2015; available at http://www.ctia.org/your-wireless-life/how-wireless-works/wireless-quick-facts. Comments of CTIA, by Michael F. Altschul, Scott K. Bergmann and Krista L. Witanowski, *Inquiry Concerning the Deployment of Advanced Telecommunications Capability to All Americans in a Reasonable and Timely Fashion, and Possible Steps to Accelerate Such Deployment Pursuant to Section 706 of the Telecommunications Act of 1996, as Amended by the Broadband Data Improvement Act*, GN Docket No. 14-126 (September 4, 2014).

30 *Revision of Part 15 of the Commission's Rules to Permit Unlicensed National Information Infrastructure (U-NII) Devices in the 5 GHz Band*, First Report and Order, ET Docket No. 13-49, FCC 14-30 (rel. April 1, 2014). See also Chris Spain, "What, Why, Where, When, How: The New FCC Ruling Around 5 GHz," Cisco Blog, May 9, 2014, accessed February 9, 2015; available at http://blogs.cisco.com/wireless/what-why-where-when-how-the-new-fcc-ruling-around-5-ghz.

31 "Challenges and Opportunities in the 5 GHz Spectrum Band," U.S. House Committee on Energy and Commerce, Subcommittee on Communications and Technology (November 13, 2013) (Testimony of

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As regulators have expanded the available spectrum, Wi-Fi technology has continued to improve. The latest version of the Wi-Fi standard (802.11ac) allows data to be carried at more than 1 Gbps—a billion bits per second—and offers higher spectrum efficiency than the earlier versions. (802.11ac operates only in the 5 GHz band because it requires signals wider than those available at 2.4 GHz.) The 802.11ac standard also supports multi-user MIMO—a spatial multiplexing technology that doubles or triples spectrum efficiency with today's technology and promises additional efficiency gains in the future.[32]

The IEEE and ANSI adopted the final version of 802.11ac in December 2013, and hundreds of products that take advantage of it are already available.[33] The recently released Apple iPhone 6, tens of millions of which have already been purchased, includes the 802.11ac capability (as noted earlier, the iPhone 6 does not include TV white space capability).[34]

Another new IEEE standard, 802.11ad, provides for very high-speed data transfer at 60 GHz. Development of this standard—sometimes known as WiGig—began at the end of 2008, and ANSI approved it in December 2012. Although 802.11ad has been adopted less rapidly than 802.11ac, Dell claims to have sold more than a million laptops with 802.11ad capability installed,

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Thomas F. Nagel, Senior Vice President, Comcast Corporation): p. 2; available at http://docs.house.gov/meetings/IF/IF16/20131113/101359/HHRG-113-IF16-Wstate-NagelT-20131113-U1.pdf.

32 Multi-user (MU) MIMO chipsets are available today. See "Qualcomm Innovates to Optimize Spectrum Usage with Revolutionary MU-MIMO for Wi-Fi," Qualcomm Inc. press release, April 3, 2014, accessed November 24, 2014; available at https://www.qualcomm.com/news/releases/2014/04/03/qualcomm-innovates-optimize-spectrum-usage-revolutionary-mu-mimo-wi-fi.

33 The Wi-Fi Alliance's web page lists more than 1,000 products as being Wi-Fi CERTIFIED™ as an 802.11ac product, and Wikipedia lists 11 wireless handsets, including the Apple iPhone 6, that have 802.11ac capability built into them. Some products were commercialized even before final approval of 802.11ac, based on draft versions of the standard.

34 Apple touts the fact that its iPhone 6 has 802.11ac capability. According to Apple's iPhone 6 product page, "With new support for 802.11ac, you'll experience up to 3x faster Wi-Fi than with 802.11n [the earlier Wi-Fi standard]." See "iPhone 6," Apple Inc., accessed November 24, 2014; available at https://www.apple.com/iphone-6/connectivity/.

and Intel recently announced that its new Core M processor will support wireless docking with WiGig.[35] Popular Science listed WiGig in its list of “Best of What’s New” for 2014.[36]

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35 “Intel Launches the Intel® Core™ M Processor,” *Intel Newsroom*, September 5, 2014; available at http://newsroom.intel.com/community/intel_newsroom/blog/2014/09/05/intel-launches-the-intel-core-m-processor.

36 Lindsey Kratochwill and Matt Safford, “Best of What’s New: WIGIG, The Fastest Wireless,” *Popular Science*, October 31, 2014, accessed November 20, 2014; available at http://bestofwhatsnew.popsci.com/wigig.

III. Prospects for the 600 MHz Band: "Wi-Fi on Tranquilizers"

The FCC and a number of high-tech firms assert that the propagation characteristics of the 600 MHz band will allow unlicensed devices to operate more cheaply and effectively there than they can in the higher frequency bands where most unlicensed activity now occurs.[37] Citing the skyrocketing consumer demand for Wi-Fi-enabled devices, they argue that the authorization of unlicensed operations in the 600 MHz band will provide a much-needed alternative to the higher-frequency bands, which they say are becoming increasingly congested with Wi-Fi traffic.[38] They also assert that allowing unlicensed use of the 600 MHz band will power a new wave of mobile broadband innovation, by giving device designers better quality spectrum and a range of frequencies from which to choose.[39]

These advocates point to a range of applications that will get an economic boost from unlicensed access to the 600 MHz band. One category of applications relies on short-range data transfer—essentially, local area networks (LANs), such as those enabled by Wi-Fi and Bluetooth, that use unlicensed spectrum to connect wireless devices in a home or office to the Internet (e.g., Wi-Fi hot spots). In addition to next-generation Internet access in homes and businesses, the advocates emphasize the rapid growth of several relatively new short-range data transfer applications that rely almost entirely on unlicensed spectrum. These include "cellular offload," referring to wireless carriers' use of Wi-Fi to offload Internet-related data traffic from their congested (licensed) networks; machine-to-machine (M2M) connectivity (also called the "Internet of Things"), such as RFID tags, smart grid implementation (automated meter readers), and other

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37 It is often claimed that lower spectrum bands have superior propagation characteristics because longer radio waves can travel farther and penetrate solid objects more easily than can the shorter waves found at higher bands. Although radio waves at lower frequencies generally get better range, they do not necessarily get better penetration, as anyone who has driven into a highway tunnel with their car radio on can attest: the AM signal (lower band) typically disappears while the FM signal (higher band) survives. The arguments in this report do not turn on this more complex understanding of signal penetration, however. Rather, our argument is that, however good the propagation characteristics of the 600 MHz guard bands, that source of advantage is more than offset by other, disadvantageous, features of those frequencies.

38 Not all spectrum experts agree with this assertion. See for example, J. Pierre de Vries, Ljiljana Simic, Andreas Achtzehn, Marina Petrova, and Petri Mähönen, "The Emperor Has No Problem: Is Wi-Fi Spectrum Really Congested?," TPRC 41: The 41st Research Conference on Communication, Information and Internet Policy, October 9, 2013; available at http://ssrn.com/abstract=2241609.

39 Comments of Google Inc. and Microsoft Corporation, *Expanding the Economic and Innovation Opportunities of Spectrum Through Incentive Auctions,* GN Docket No. 12-268 (Jan. 25, 2013).

forms of automated data exchange between networked devices; and "cable metronets," which are large, organized networks of Wi-Fi access points that cable companies have created in selected cities to provide their subscribers with Internet access outside the home.[40]

A second set of applications that the advocates claim will benefit from unlicensed access to the 600 MHz band is long-range voice and data communications. They argue that Wireless Internet Service Providers (WISPs) can provide cost-effective broadband service in rural and low-population areas by using unlicensed spectrum, because they can avoid the high cost of last-mile cable or licensed spectrum. They claim that the availability of 600 MHz band spectrum with its advantageous propagation characteristics will facilitate the process of extending coverage to areas that are unserved or underserved by traditional Internet Service Providers.[41]

Recall that supporters made the same claims about unlicensed access to the TV white space, and yet the market response has been anemic. Moreover, the 600 MHz guard bands face even greater impediments to investment than does the TV white space because the FCC's power restrictions will be considerably more stringent. If "Wi-Fi on steroids" is the promise for unlicensed use of the 600 MHz guard bands, we believe the reality will be closer to "Wi-Fi on tranquilizers."

A. Short-Range Data Transfer

For short-range data transfer applications, including cellular offload, M2M communications, and cable metronets, unlicensed spectrum in the 600 MHz band will be substantially inferior to the existing unlicensed bands at 2.4 GHz and 5 GHz. The principal reason is capacity: an unlicensed device operating in the 600 MHz band will have a data rate that is only about one-tenth to one-hundredth the data rate of a Wi-Fi device operating in the existing unlicensed bands. For most applications, that handicap will trump any propagation advantages that the 600 MHz band may offer. As one wireless expert wrote in his blog on the changing definition of "beachfront" spectrum, "[i]t's not the distance, it's the volume."[42]

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40 Comments of Google Inc. and Microsoft Corporation, *op. cit.*, pp. 21-28.

41 *Ibid.,* pp. 16-18.

42 Peter Rysavy, "Learn How Technology Will Turn Less Desirable Airwaves Into 'Beachfront' Spectrum," *Gigaom,* June 28, 2013; available at http://gigaom.com/2013/06/28/learn-how-technology-will-turn-less-desirable-airwaves-into-beachfront-spectrum. See also Peter Rysavy, "White Spaces Networks Are Not 'Super' Nor Even Wi-Fi," *Gigaom,* March 17, 2013; available at https://gigaom.com/2013/03/17/white-spaces-networks-are-not-super-nor-even-wi-fi/.

In part, this handicap stems from the basic physics of spectrum: lower bands have generally better range but less bandwidth than higher bands.[43] In addition, limitations specific to the 600 MHz and 700 MHz bands will likely constrain manufacturers to the design of devices that operate in a single six-megahertz channel.[44] By comparison, Wi-Fi devices that operate at 2.4 GHz and 5 GHz use channels that have up to 80 megahertz—and may have up to 160 megahertz—of bandwidth.[45] Thus, the 600 MHz guard band devices will operate in a channel that is no more than one-twenty-fifth the size of the widest channels in the higher unlicensed bands, and their data rate will be correspondingly inferior.

Granted, there are steps that a manufacturer could take to compensate for the severe limitation on bandwidth in the TV bands—for example, dynamic channel bonding. But those steps would require putting more transmitters and receivers in the consumer device, adding to the complexity and expense of devices whose commercial appeal is their simplicity and low cost.

In addition to providing greater raw bandwidth, the higher frequencies can take better advantage of sophisticated antennas, including MIMO technology. MIMO represents a new frontier for expansion of wireless capacity, because it allows radio signals to propagate along multiple paths, creating simultaneous parallel transmissions. However, antennas must be separated from one another to achieve the desired capacity gain, and the lower the band, the greater the necessary

[43] The advantage that lower spectrum bands have in terms of range is often overstated. In fact, if line-of-sight conditions prevail and directional antennas are used at both ends of a wireless link, higher frequencies actually provide better range. For this reason, engineers who design radio links between satellites often use the highest frequency available.

[44] Title VI of the Middle Class Tax Relief and Job Creation Act of 2012 (Spectrum Act), which authorized the voluntary incentive auction of the 600 MHz broadcast spectrum, contemplated the operation of unlicensed devices in the post-auction guard bands. However, it explicitly directed the FCC to make these bands no larger than technically reasonable to prevent harmful interference to licensed services. In addition, the FCC's proposed rules for unlicensed operations in the 600 MHz guard bands contemplate the use of a six-megahertz channel. Thus, the market will likely provide devices that operate in a single six-megahertz channel as a lowest common denominator.

[45] Capacity is a function of power as well as bandwidth. However, with LAN-type devices that operate at short ranges (e.g., a Wi-Fi connection within a home), there is little loss of signal strength between the transmitter and the receiver. Thus, bandwidth, not power, is usually the limiting factor in the performance of the devices.

separation distance. Thus a tablet or smartphone designed to operate at 2.4 GHz or 5 GHz will be far more able to take advantage of MIMO than one designed to operate at 600 MHz.[46]

Because the unlicensed bands at 2.4 GHz and 5 GHz offer greater bandwidth and better performance with MIMO, equipment manufacturers that require high-burst data rates or high throughput will almost certainly choose those bands over the 600 MHz guard bands. Consider a manufacturer looking to design a system for wireless distribution of an HDTV or ultra-HDTV signal within the home. It would be difficult, if not impossible, for such a system to achieve the necessary speed (say, 100 Mbps) using 600 MHz guard band spectrum, given the restriction on bandwidth (six-megahertz channels). By contrast, manufacturers have for years produced equipment that operates at 2.4 GHz and 5 GHz at data rates that exceed 100 Mbps.

In part because they make possible such high data rates, the 2.4 GHz and 5 GHz bands have spawned a huge installed base of interoperable equipment (devices) designed for short-range data transfer. Manufacturers and users of this equipment, some of which is known by the name of the relevant IEEE family of standards (802.11), benefit from the large scale and network economies and the resulting bandwagon effect. The IEEE has developed two standards for the TV white space, and those standards will cover devices designed to operate in the 600 MHz unlicensed spectrum as well. However, because the market for equipment that operates at 2.4 GHz and 5 GHz is so dominant and the bandwagon effect so strong, the incentives for manufacturers to develop devices for the new bands are likely to be weak.[47]

In addition to the bandwidth handicap, which is largely physical in nature, unlicensed use of the 600 MHz guard bands faces a major regulatory handicap. Unlicensed devices attempting to use the 600 MHz band will need to protect licensed operations in that band. The additional hardware (filters) necessary to accomplish this will increase cost and complexity.

A related regulatory restriction has to do with signal power. The FCC has proposed that unlicensed devices operating in the 600 MHz guard bands be limited to 16 dBm EIRP, or (less

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46 A convenient rule-of-thumb says to separate antennas by at least one-half wavelength. At 2.4 GHz, one-half wavelength is only 2.5 inches, whereas at 600 MHz, it is 10 inches. It would be difficult to achieve a 10-inch separation even on a laptop, and it would be almost impossible to achieve it on anything smaller, such as a smartphone or camera.

47 For an analysis of the power of the bandwagon effect on technology adoption and deployment, see Jeffrey H. Rohlfs, *Bandwagon Effects in High-Technology Industries*. Cambridge, MA: MIT Press, 2003.

precisely) 40 milliwatts (mW), of power.[48] By contrast, the FCC rules permit unlicensed devices at 2.4 GHz to transmit with a total power of one watt and to use directional antennas to increase radiated power (in one direction) to four watts, or 100 times the 40 mW power limit for unlicensed devices in the 600 MHz guard bands. (The power limits at 5 GHz are more complex but can be as high as those at 2.4 GHz.) We calculate that the 16 dBm EIRP/40 mW limitation on power will eliminate much or all of the advantage that 600 MHz guard band devices have to offer over 2.4 GHz and 5 GHz devices in terms of increased range.[49]

The implication of this calculation is significant. In our 2007/2008 analyses of the FCC's proposal to allow unlicensed use of the TV white space, we concluded that the TV white space might

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[48] EIRP stands for equivalent isotropically radiated power, and it is stated in terms of decibels (dB) over a reference power—in this case milliwatts (m). EIRP refers to the signal strength created by a theoretical antenna that distributes power at a given level equally in all directions.

[49] The Friis propagation formula is the basis for many of the claims made for the superior propagation properties of the TV bands: it predicts that, all else equal, a signal transmitted at 600 MHz will be received at about 100 times the power of one transmitted at 5 GHz (i.e., it will have a power advantage of 100). Based on that formula, a 40 mW signal transmitted at 600 MHz will have the same received strength as a 4-watt signal transmitted at 5 GHz, which is a feasible power level for that band. (Although the FCC rules governing the power level of unlicensed devices operating at 5 GHz are complex, in some parts of the 5 GHz band, devices can transmit at 4 watts, and point-to-point connections can transmit at even higher power levels.) Thus, the FCC's proposed power limit of 40 mW will cancel most if not all of the advantage that 600 MHz guard band devices have over unlicensed devices operating at 5 GHz. By comparison, the all-else-equal power advantage of the 600 MHz band over the 2.4 GHz band is only 16, which means that a 40 mW signal transmitted at 600 MHz will have the same received strength as a 640 mW signal transmitted at 2.4 GHz (16 X 40 = 640). But since 2.4 GHz devices are allowed to transmit at up to 1 watt, the 600 MHz guard band devices will have absolutely no power advantage over them. Granted, this calculation does not take into account other differences between the existing unlicensed bands (2.4 GHz and 5 GHz) and the 600 MHz guard bands, including antenna gain, building penetration, MIMO performance, Fresnel zone size and vegetation penetration. However, with one notable exception (vegetation penetration), most of those differences favor the 2.4 GHz and 5 GHz bands.

Although proponents of TV white space often tout building penetration as an advantage of the TV bands, the literature on this point is quite mixed: most experts find little difference in the ability of a signal to penetrate buildings at 600 MHz versus 6,000 MHz, and some studies conclude that building penetration is actually better (i.e., signal loss is less) at higher frequencies. For example, Davidson and Hill reported that, in a study of 10 buildings, the building penetration of radio signals was slightly better at 1,500 MHz than at 900 MHz. (Allen Davidson and Casey Hill, "Measurement of Building Penetration into Medium Buildings at 900 and 1500 MHz," *IEEE Transactions on Vehicular Technology,* Vol. 46, No. 1 (1997): pp. 161-168.) Similarly, Siwiak and Bahreini found that there was a steady decrease in building attenuation (signal loss) as spectrum frequency increased. See Figure 18 in I. Siwiak and Y. Bahreini. *Radiowave Propagation and Antennas for Personal Communications*. Artech House, Inc., 2007, at p. 223.

support a small market niche consisting of applications that needed only modest bandwidth but that required greater range than they could achieve at 2.4 GHz.[50] If 600 MHz guard band devices lack that advantage—that is, if they offer only about the same range as higher-powered Wi-Fi devices (and lack the installed base of such devices)—it is hard to envision what their market niche would be.

B. Long-Range Communications

The provision of unlicensed spectrum in the 600 MHz band is also unlikely to promote significant investment in the infrastructure necessary for long-range voice and data communications, but for different reasons than those that will impede investment in short-range applications. Recall that for short-range applications, the 600 MHz guard bands will be inferior to the existing unlicensed bands. By contrast, for long-range applications—the applications for which the 600 MHz band is better suited—the unlicensed 600 MHz guard bands will be inferior to licensed spectrum.

Two substantial limitations will impede investment in unlicensed use of the 600 MHz guard bands for long-range communications. The first is the threat of interference from short-range unlicensed devices as well as licensed operations in bands adjacent to the 600 MHz guard bands. This is basic physics: to the extent that radio signals propagate better in the lower bands, so too does interference. The threat of interference will impose a cost on unlicensed service providers that licensed operations do not typically face.[51]

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[50] For example, we said TV white space devices would support low-cost cordless phones in settings that currently require multiple base stations to get good coverage (e.g., farms and university and industrial campuses). We also said that, because of their propagation characteristics, the TV bands might be attractive for moderate capacity, point-to-point links such as those used to connect Wi-Fi hot spots to backbone networks or for the kind of opportunistic, point-to-point links that are needed in emergencies.

[51] The interaction between licensed wireless microphones and unlicensed guard band devices is another potential source of interference, and the interference could flow both ways. To elaborate, the FCC proposes in the 600 MHz Unlicensed NPRM to set aside four megahertz of spectrum in the duplex gap exclusively for licensed wireless microphones, and this four-megahertz portion of the duplex gap is separated by only one megahertz from the adjacent LTE downlink block. See 600 MHz Unlicensed NPRM at para. 94. If the signals from the licensed wireless microphones cause interference to unlicensed operations, the unlicensed operator will have no recourse because its operations are secondary to the licensed operations. And if signals from unlicensed guard band devices cause interference to licensed wireless microphone operations, the unlicensed devices will have to cease operation altogether. The FCC has indicated that it believes the risk is low that unlicensed signals will

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A second, and even more substantial, limitation on unlicensed use of the 600 MHz guard bands for long-range communications is the FCC's necessarily strict limit on power levels. A power limit of 40 mW is sufficient for a short-range connection for a personal/portable device such as a tablet computer or a cordless phone. It is entirely insufficient for long-range services such as rural broadband access, however.[52] Simply stated, unlicensed systems operating in the 600 MHz guard bands will not be able to provide rural broadband access on a scale that has any meaningful impact.

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interfere with licensed wireless microphones. But even a low risk will reduce the incentive for a manufacturer to produce devices for unlicensed operation in the guard bands.

52 A quick reading of certain comments in this proceeding might leave one with the impression that proponents of unlicensed use of the guard bands believe that such use offers an opportunity to expand rural broadband access. For example, the Wireless Internet Service Providers Association (WISPA) stated that "the WISPA Comments documented the importance of unlicensed spectrum to the extension of affordable fixed broadband services to rural, unserved and underserved areas of the country." Reply Comments of The Wireless Internet Service Providers Association, *Expanding the Economic and Innovation Opportunities of Spectrum Through Incentive Auctions*, *Revisions to Rules Authorizing the Operation of Low Power Auxiliary Stations in the 698-806 MHz Band*, *Public Interest Spectrum Coalition, Petition for Rulemaking Regarding Low Power Auxiliary Stations, Including Wireless Microphones, and the Digital Television Transition*, and *Amendments of Parts 15, 74 and 90 of the Commission's Rules Regarding Low Power Auxiliary Stations, Including Wireless Microphones*, GN Docket No. 12-268, WT Docket No. 08-166, WT Docket No. 08-167 and ET Docket No. 10-24 (March 12, 2013), at p. 2. However, WISPA made that statement in the context of the 4-watt power limit for fixed TV white space devices and, more generally, the much higher limits on emitted power at 2.4 GHz and 5 GHz. There should be no misunderstanding: given the FCC's necessarily strict (proposed) limits on the power level at which they can transmit signals (40 mW), unlicensed systems that operate in the 600 MHz guard bands will not be able to provide rural broadband access on a scale that has any economic impact.

IV. Technical Analysis of the Potential for Interference from Unlicensed Use of the 600 MHz Guard Bands

In addition to being ineffective (fatal flaw #1), the FCC's policy to allow unlicensed operations in the 600 MHz guard bands will be downright harmful because interference from those operations are likely to have an adverse impact on licensed mobile LTE services (fatal flaw #2). The prospect of this interference, by lowering the value of the affected 600 MHz spectrum, could profoundly damage the incentive auction.

In this section, we look at the cause of interference from unlicensed operations in the 600 MHz guard bands and at its potential magnitude as measured by the "interference range"—the distance from an unlicensed guard band device that an LTE handset can be located and still experience harmful interference. We examine the FCC's technical analysis, which found that the interference range could extend up to 20 feet. Although this finding is itself disturbing, it actually understates the problem. Key assumptions about the magnitude of the "path loss" (loss of signal strength as the unlicensed signal travels to the LTE handset) are based on conditions that differ from the ones in the case at hand. When we modify the assumptions to reflect what we believe are the appropriate conditions, the estimated interference range is significantly larger (45 feet to 75 feet).

A. Interference by Unlicensed Devices: Background

Interference will occur when a signal emitted by an unlicensed device (including a wireless microphone) that is operating in the 600 MHz guard bands interferes with the ability of a mobile phone, tablet, or laptop that is using licensed LTE at 600 MHz to receive its intended signal. For this to occur, the unlicensed device and the LTE equipment will need to be physically proximate, although the exact interference range depends on factors such as power limits and "spectrum proximity" (i.e., frequency separation). Spectrum proximity is also key to understanding the impact of the interference: the LTE downlink blocks adjacent to the guard bands (including the duplex gap) will experience the most severe interference, although non-adjacent blocks may be harmed as well.[53]

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[53] According to a recent analysis by CTIA, LTE bands that are not adjacent to the guard bands will experience interference at "similar levels" to what LTE bands directly adjacent to the guard bands will experience. See Comments of CTIA, *Amendment of Part 15 of the Commission's Rules for Unlicensed*

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The severity of interference is a measure of the impact on licensed LTE operations. At the extreme, the interference could create a coverage hole, meaning that the most proximate LTE equipment would not be able to use the affected LTE block at all. For example, interference from an unlicensed guard band device mounted in the ceiling of a Starbucks coffee shop could prevent use of the adjacent LTE spectrum block by any LTE equipment close to the device. Even if the affected LTE block remains functional, interference could reduce its capacity. For example, LTE devices in the Starbucks might be limited to one-half of their maximum download speed.

B. FCC Analysis of Potential Interference from Unlicensed Guard Band Devices

In the 600 MHz Unlicensed NPRM, the FCC proposes two rules designed to reduce the likelihood that unlicensed guard band devices would interfere with the operation of wireless equipment using licensed LTE at 600 MHz. The first rule involves power limits: as discussed earlier, the FCC is proposing to limit unlicensed guard band devices to a power level of 16 dBm EIRP or 40 mW. The second rule involves frequency separation: the proposed rule calls for 600 MHz guard band devices to operate in six-megahertz sections of the duplex gap and the larger guard bands such that there is a three-megahertz separation, or buffer, between the unlicensed guard band operations and the nearest licensed LTE downlink (i.e., receive) services.[54]

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Operations in the Television Bands, Repurposed 600 MHz Band, 600 MHz Guard Bands and Duplex Gap, and Channel 37, *Amendment of Part 74 of the Commission's Rules for Low Power Auxiliary Stations in the Repurposed 600 MHz Band and 600 MHz Duplex Gap*, *Promoting Spectrum Access for Wireless Microphone Operations*, and *Expanding the Economic and Innovation Opportunities of Spectrum Through Incentive Auctions*, ET Docket No. 14-165, GN Docket 14-166 and GN Docket 12-268 (February 4, 2015) ("Comments of CTIA"). In the economic analysis described in this report, we assume, conservatively, that the interference from unlicensed operations affects only the adjacent bands. To the extent that the interference extends to non-adjacent bands, our results understate the adverse impact it will have on the value of the 600 MHz spectrum and the outcome of the incentive auction.

54 Under the FCC's proposed band plans for the post-auction 600 MHz band, there are three possibilities for the size of the (traditional) guard band: 11 megahertz, nine megahertz and seven megahertz. If the guard band is 11 megahertz or nine megahertz, unlicensed guard band devices would operate in the six megahertz farthest from the adjacent LTE downlink block, thus allowing at least three megahertz of separation from licensed LTE services. If the guard band is only seven megahertz, it likely would be off limits to unlicensed devices because there would be only one megahertz of separation from LTE services. The band plans also include three-megahertz buffer zones around Channel 37, which we refer to as "guard bands." Although the FCC has proposed that these three-megahertz guard bands (as

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The 600 MHz Unlicensed NPRM also describes the analysis that the FCC undertook to estimate the potential for unlicensed guard band operations to interfere with LTE services at 600 MHz. Using a standard wireless signal propagation model (FCC TM 91-1), the FCC specified (i.e., assumed) the value of key variables that would affect the performance of the unlicensed devices, including the proposed 40 mW power limit and the three-megahertz frequency separation from licensed LTE services. The FCC also made assumptions about the amount of signal strength that the unlicensed signal would lose as it traveled to the LTE receiver ("path loss"). Based on the results of its analysis of a representative scenario, the FCC estimated that an unlicensed device could interfere with the operation of a mobile phone using LTE at 600 MHz if the two devices were less than seven meters (or about 20 feet) apart, although the FCC qualified its conclusion by referring to vague countervailing factors.

1. The FCC's Estimate of the Interference Range Will Give Bidders Pause

The conclusion of the FCC analysis—that 600 MHz guard band devices could cause interference to LTE handsets as far as 20 feet away—is likely to give bidders serious pause. Granted, the interference problem will be proportionate to the deployment and use of the unlicensed devices. Thus, if the market shows little interest in the devices, the problem may be limited. However, if the incremental cost of building such a device turns out to be low, future versions of the commercial and residential Wi-Fi hotspots that now provide access to the 2.4 GHz and 5 GHz bands may include the hardware necessary to provide access to the 600 MHz unlicensed guard bands so as to give users another option. As discussed below, the addition of that hardware inside access points could result in interference even if few people exercised the option to use an unlicensed guard band device.

To explain, Wi-Fi access points normally transmit a beacon signal every tenth of a second to alert user devices to their presence; although the beacon signal is short, it is generally transmitted at maximum power (40 mW in the case of a 600 MHz guard band signal). Beacon transmissions designed to alert devices to the presence of a guard band-enabled access point could interfere with LTE devices directly. Moreover, such interference could cause the LTE equipment to signal

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well as Channel 37) be used for unlicensed operations, they are not affected by the NPRM proposal on frequency separation.

to the network that the wireless link is impaired (i.e., that it has reduced capacity) and that the network should adjust accordingly.[55]

In sum, even if 600 MHz guard band devices themselves see little use, the enabling technology will generate interference if it gets bundled into Wi-Fi hotspots. Using the FCC's own estimate (20 feet), if a Starbucks coffee shop has a guard band-enabled Wi-Fi access point in its ceiling, any of the customers whose LTE mobile phone provider relies on an affected band could experience harmful interference.

Moreover, should demand for 600 MHz guard band devices materialize, it would likely be in dense, urban areas where demand for licensed networks and Wi-Fi frequencies is highest and where access to LTE networks is most constrained. Thus, the potential for 600 MHz guard band devices to cause harmful interference is the greatest in those geographic areas where it would do the most damage.

2. The FCC's Estimate of the Interference Range Understates the Problem

Although the FCC's estimate of the interference range (up to 20 feet) is disturbingly large, it understates the true risk of the interference.[56] Specifically, the FCC's two assumptions about the magnitude of the path losses are based on conditions that differ from the ones in the case at hand. When those assumptions are modified to reflect what we believe are the appropriate conditions, the estimated interference range is significantly larger.

The first problematic assumption has to do with the performance of LTE filters. The LTE standards organization, known as the Third Generation Partnership Project (3GPP), requires that LTE handsets have filters sufficiently robust that they can screen out unwanted signals, such as

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55 Beacon signals are not the only signals that would be transmitted at high power levels; the same would be true for signals from guard band devices that carry user data. To explain, Wi-Fi uses adaptive modulation and coding, which means that Wi-Fi devices transmit at a higher data rate where possible. One relevant factor is power levels: devices designed to operate at higher power levels can transmit at higher data rates. Given that the 600 MHz unlicensed devices will have to operate in narrow (6-megahertz) channels, they will almost certainly be designed to operate at the highest possible power level, so as to maximize their (limited) data rate.

56 Elsewhere in the 600 MHz Unlicensed NPRM, the FCC says that its interference analysis looked at a worst-case scenario and did not consider several factors that would tend to reduce the seven-meter (20-foot) interference range. However, we examine those factors below (see subsection D, "The FCC's 'Prebuttal'") and find them to be less than compelling.

the ones guard band devices would create, that are 33 decibels (dB) stronger than the desired signal. By contrast, the FCC's model assumes that LTE handsets operating at 600 MHz will be able to reject interference from unlicensed devices that is 43 dB stronger than the desired signal—or 10 dB more than the 3GPP standard requires. However, that additional 10 dB—which represents an order of magnitude improvement in performance—will come at a cost: the manufacturer of the LTE handset will have to spend more to build the handset, and it may have to make other undesirable tradeoffs—e.g., increasing the size and weight of the handset or reducing the battery life.

Although it may be reasonable to expect LTE filters to perform slightly better than the 3GPP standard requires, the FCC's assumption of an order of magnitude in additional performance is unwarranted without strong supporting justification. That justification is lacking in the FCC's 600 MHz Unlicensed NPRM. Instead, it appears that the FCC based its assumption on an ex parte filing in which Broadcom said that LTE filters in a few phones were performing at that level.

The second problematic assumption has to do with the loss of unlicensed signal strength due to obstruction from various factors, including the user's head or hand ("head-body loss"), antenna mismatch, and multipath/shadowing (e.g., obstruction from a wall or other object). The greater the loss of signal strength from obstruction, the less of a problem interference from 600 MHz guard band devices will pose for LTE mobile phones.

In its propagation analysis, the FCC assumed that obstruction would cause a 15 dB loss of strength in the signal emitted by a 600 MHz guard band device as it traveled to an LTE mobile phone. However, as support, the FCC cited a 2008 study of a similar case by its Office of Engineering and Technology (OET); in that study, OET concluded that obstruction would cause a loss of signal strength totaling 11.5 dB, including 6 dB for head-body loss, 2 dB for antenna mismatch and 3.5 dB for multipath/shadowing. The 600 MHz Unlicensed NPRM does not explain why the FCC's analysis of 600 MHz guard band devices used a higher loss estimate than the one the 2008 OET study produced (15 dB versus 11.5 dB). This is particularly significant considering that, in our estimation, 600 MHz guard band devices would experience less, not more, signal loss than the devices that the OET studied in 2008.

To elaborate, the 2008 OET study looked at a case in which there were two handheld devices (a transmitter and a receiver), each of which contributed an estimated 3 dB of head-body loss, for a total of 6 dB of loss. In the case of 600 MHz guard band devices, although the LTE device will in many cases be handheld (i.e., a mobile phone), the guard band device will generally be mounted on a wall or ceiling, where head-body obstruction will not be present. (Consistent with that scenario, the FCC's propagation analysis assumed that the unlicensed guard band device would be located 3 meters (10 feet) above ground.) Thus, a reasonable estimate of the head-body loss for signals from 600 MHz guard band devices is half of what OET found in 2008, or 3 dB.[57]

3. Recalculation of the Interference Range

In sum, the estimates for additional loss (loss due to obstruction) that the FCC used in its propagation analysis—analysis on which the 600 MHz Unlicensed NPRM is based—are highly questionable at best. Below, we recalculate the likely interference range using different values for the two path loss assumptions.[58] Under each of two alternative scenarios, we find that the interference range would be significantly larger than that estimated by the FCC. (See Table 1)

Scenario Z is the FCC scenario, with its two key path loss assumptions (10 dB of additional loss due to high performing filters and 15 dB loss from obstruction) and the resulting estimate of a 20-foot interference range. For Scenario A, we assume that LTE filters would outperform the 3GPP standard by a more modest 3 dB and that obstruction loss would total only 8.5 dB (OET's 11.5 dB estimate minus 3 dB because only one of the two devices is handheld). Using those values, and leaving everything else in the FCC's propagation model the same, we find that unlicensed devices operating in the 600 MHz guard bands would cause interference for wireless handsets up to 75 feet away. For Scenario B, we roughly "split the difference" between Scenario A and the FCC

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57 In reality, many of the LTE "devices" that experience interference from unlicensed guard band devices will be tablets and laptops, which cause less head-body obstruction than mobile phones. Thus, even 3 dB may overstate the amount of head-body loss in the current case. Nevertheless, to be conservative, we use 3 dB in our analysis.

58 Separate comments filed recently by CTIA and Qualcomm support our conclusion that interference would extend well beyond the 20 feet estimated by the FCC. In those comments, CTIA and Qualcomm report the results of extensive testing of LTE receivers. Both CTIA and Qualcomm conclude that operation of white space devices and wireless microphones under the proposed rules would create interference and that substantial revisions would be required to protect against interference. See Comments of CTIA (February 4, 2015); and Comments of Qualcomm Incorporated, *Amendment of Part 15 of the Commission's Rules for Unlicensed Operations in the Television Bands, Repurposed 600 MHz Band, 600 MHz Guard Bands and Duplex Gap, and Channel 37*, *Amendment of Part 74 of the Commission's Rules for Low Power Auxiliary Stations in the Repurposed 600 MHz Band and 600 MHz Duplex Gap*, and *Expanding the Economic and Innovation Opportunities of Spectrum Through Incentive Auctions*, ET Docket No. 14-165, GN Docket No. 12-268 (February 4, 2015).

scenario and assume that LTE filters would outperform the 3GPP standard by 6 dB and that obstruction losses would total 12 dB. Under that scenario, we find that unlicensed devices operating in the 600 MHz guard bands would cause interference to wireless handsets located up to 45 feet away.

Table 1: Recalculation of the Interference Range

	Scenario	Path Loss Due to High Performing Filters	Path Loss Due to Obstruction	Interference Range
		(dBs)	(dBs)	(feet)
[1]	Z	10	15	20
[2]	A	3	8.5	75
[3]	B	6	12	45

Sources and Notes:
[1]: 600 MHz Unlicensed NPRM.
[2] and [3]: The Brattle Group

C. Interference from Unlicensed Wireless Microphones at 600 MHz

In the 600 MHz Unlicensed NPRM, the FCC proposes that unlicensed wireless microphones be allowed to operate (a) in the same six-megahertz portion of the duplex gap as unlicensed guard band devices and (b) across guard bands of any size (including the seven-megahertz guard bands that would be off limits to unlicensed guard band devices under the 600 MHz Unlicensed NPRM) except for a one-megahertz segment at the upper end that would act as a buffer between the unlicensed wireless microphone operations and licensed LTE downlink services at 600 MHz. The FCC also proposes to limit the power of unlicensed wireless microphone systems to 20 mW, or half of the power limit for unlicensed guard band devices.

Under the FCC's proposed rule, the frequency separation between LTE services and unlicensed wireless microphones (one megahertz) would be far less than the separation between LTE services and unlicensed guard band devices (three megahertz). The reduced separation means that LTE mobile equipment operating at 600 MHz will have even less interference protection from unlicensed wireless microphones than from unlicensed guard band devices. This is a particular concern given that wireless microphones emit more concentrated power.

To elaborate, whereas the power transmitted by an unlicensed guard band device will be spread evenly across the six megahertz in which it operates, the power transmitted by a wireless microphone will be concentrated in a fraction of a megahertz. Thus, a 20 mW unlicensed wireless microphone that is operating one megahertz (or even two or three megahertz) away from LTE mobile equipment will cause more harmful interference than a 40 mW unlicensed guard band device that is operating three or more megahertz away.[59]

D. The FCC's "Prebuttal"

In a lengthy paragraph in its 600 MHz Unlicensed NPRM, the FCC tries to anticipate the concerns raised by its finding that unlicensed guard band devices could cause interference to wireless handsets located up to 20 feet away. The theme of the paragraph is that the interference analysis looked at a worst-case scenario and did not consider several factors that would tend to reduce the interference range. Potential bidders may not be reassured by the Commission's "prebuttal," however.

First, the FCC stresses that an unlicensed device would automatically limit its operating power to the minimum necessary, which means that such devices would often be transmitting less than the maximum power (40 mW) on which the Commission based its analysis. However, Wi-Fi access points generally transmit beacon signals at maximum power and, as we have noted, those signals will go out 10 times a second regardless of whether or not anyone is using the 600 MHz guard band devices themselves. Moreover, when users do take advantage of 600 MHz guard band spectrum, it will be because they are operating at a greater distance from the access point and thus cannot get access to the higher-capacity (but shorter range) Wi-Fi bands at 2.4 GHz and 5 GHz. Such users, operating at greater distances, will require higher power.

Second, as an explanation for why some interference may not prove harmful, the FCC highlights the importance of "transmission protocols and modulation schemes which are designed to facilitate operations when conditions are less than ideal by incorporating coding, bit interleaving, and retransmission events when necessary."[60] While this statement is technically correct, it ignores the fact that there is no free lunch: such compensatory actions use up system capacity,

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59 This is also an issue for licensed wireless microphones. As noted earlier, the FCC proposes to set aside a block of spectrum in the duplex gap exclusively for licensed wireless microphones, and it is separated by only one megahertz from the adjacent LTE downlink block.

60 600 MHz Unlicensed NPRM, para. 85.

which reduces the productivity of a wireless carrier's investment and thus makes the corresponding spectrum less valuable than it would otherwise be.

Third, the FCC expresses confidence that manufacturers will use the time prior to networks being deployed to improve filter technology and designs to minimize the potential for harmful interference. While the Commission's optimism may be justified, bidders seeking to put the spectrum to use as soon as possible may not be so sanguine.

V. Impact of Interference on Network Capacity and Spectrum Value

In Section IV, we looked at the interference range as one measure of how unlicensed operations in the 600 MHz guard bands would affect LTE operations. In this section, we look at another measure—and the one that is most relevant to network operators: the fraction of capacity, or productivity, that a licensed LTE network at 600 MHz would lose if LTE handsets were subject to harmful interference from unlicensed operations. First, we identify a plausible range of interference levels that an LTE network could experience as a result of unlicensed operations in the 600 MHz guard bands. Then, based on our analysis of an LTE network in a band similar to 600 MHz, we quantify how these varying levels of interference, and the related capacity loss, would affect the market value of the affected spectrum.

A. Impact of Interference on Network Capacity

To calculate the impact of interference on system capacity, one would need to know the rate at which people will adopt and use guard band devices. If those rates are high, as proponents of unlicensed access to the guard bands predict, then the resulting interference will create a number of coverage holes, and the capacity, or productivity, of the adjacent LTE blocks will fall significantly. If the rates are low, as we believe they will be, the loss in network capacity will also be low.

Our objective is not to predict the exact level of interference, but rather to illustrate how various levels of interference would affect the value of the spectrum in the 600 MHz band. Thus, for our estimate of capacity reduction, we use a broad range: 5 percent to 35 percent. We use 5 percent as the low-end estimate because even a limited deployment of 600 MHz guard band devices will cause some amount of harmful interference. We use 35 percent as the high-end estimate because, if the reduction in capacity exceeds 35 percent, the affected 600 MHz bands will lose all value for deployment of an LTE network.[61]

[61] Granted, such a band may have some alternative use, but the band would be less valuable than if it were deployed for an LTE network, because LTE-based wireless broadband is currently the most commercially profitable use for spectrum.

B. Impact of Interference on the Market Value of Spectrum

There is a direct relationship between the capacity, or productivity, of a band of spectrum and its value in the market. Wireless carriers invest a significant amount in capital infrastructure—principally, cell sites—so that their networks will have adequate capacity (as measured in bits transmitted) and geographic coverage. Carriers value spectrum in part based on the amount of infrastructure they will need to deploy in it to achieve the required capacity in specific coverage areas: the less they need to invest in capital infrastructure, the more valuable the spectrum.

No amount of investment in a spectrum band subject to interference can restore the capacity lost due to interference. (We define a loss of capacity as an equivalent percentage reduction in the maximum number of people served per site.) However, a carrier can attempt to provide the same level of service that it would have delivered absent the interference by adding cell sites that use bands in the same network that are free from interference. Two caveats are in order. First, although established carriers have access to unaffected bands, new entrants may not have that advantage. (We discuss this concern in Section VI.) Second, it is burdensome and in some cases impossible to obtain the permits needed to construct new cell towers, which can slow the process of adding new cell sites.[62]

In short, subject to some challenges, carriers can compensate for interference by building additional cell sites that use spectrum that is free from interference. There is no free lunch, however. The construction of cell sites requires capital investment, which lowers the market value of the spectrum that is subject to interference relative to comparable spectrum that is free from interference.

To illustrate this no-free-lunch dynamic, we analyze the investment necessary to operate an LTE network in a spectrum band that is similar to the 600 MHz band. Next, we calculate the impact on investment, and in turn on spectrum value, of seven different interference levels, corresponding to incremental losses in network capacity ranging from 5 percent to 35 percent. To illustrate by taking the two extremes and the midpoint of the range, we find that a 5 percent loss of network capacity will reduce the value of spectrum in the 600 MHz band by 9 percent; a 20 percent loss of capacity will reduce spectrum value by 43 percent; and a 35 percent loss of network capacity will eliminate most (93 percent) of its value.

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62 See "Cell Tower Zoning and Permitting," Cell Tower Info.com, accessed October 7, 2014; available at http://www.celltowerinfo.com/CellTowerSiteZoning.htm.

Our findings are based on three key results. (See Appendix A for a more detailed description of the analysis and the results for all seven interference scenarios.)

First, to maintain the same level of service following a loss of network capacity, a wireless carrier would need to increase the number of cell sites by a proportional or greater than proportional amount, and the larger the loss of capacity, the more disproportional the needed response. Thus, with a 5 percent loss in network capacity, the carrier would need to increase the number of cell sites by 5 percent; with a 20 percent loss in capacity, the comparable increase would be 24 percent; and with a 35 percent loss in network capacity, the carrier would need to increase the number of cell sites by 52 percent.

To arrive at those figures, we took as a starting proxy Verizon's network, which operates using 22 megahertz in the Upper 700 MHz C Block, and we used publicly available information on the number of cell sites in the network (41,500) and the fraction of the U.S. population served (97 percent). We used county population data to estimate the number of those cell sites that provide sheer geographic coverage ("coverage" cell sites) versus the number that provide supplemental capacity in more densely populated areas ("capacity" cell sites), and we derived from those figures an estimate of the maximum number of people served per site. We adjusted our estimates on the 700 MHz system to reflect propagation differences in a system operating at 600 MHz (the total number of cell sites needed at 600 MHz would be almost the same (41,441), but there would be fewer coverage sites and more capacity sites). Then we estimated the number of additional sites needed to compensate for a loss of network capacity (i.e., a reduction in the maximum number of people served per site) ranging from 5 percent to 35 percent. With a 5 percent reduction in capacity, the carrier would need a total of 43,520 sites, which is a 5 percent increase. With a 20 percent reduction in capacity, it would need 51,382 sites, or a 24 percent increase. And with a 35 percent reduction in capacity, the carrier would need 62,978 sites, which is a 52 percent increase.

Second, by increasing costs as a share of revenue, the deployment of more cell sites would reduce a carrier's net cash flow (profit), and the larger the incremental deployment, the greater the financial impact. Thus, if a carrier needed to deploy 5 percent more cell sites (in response to a 5 percent capacity loss), its net cash flow would decrease by 9 percent. If it deployed 24 percent more sites (20 percent capacity loss), net cash flow would decrease by 43 percent. And a 52 percent increase in the number of cell sites (35 percent capacity loss) would cause net cash flow to drop by 93 percent.

To arrive at those figures, we derived cost information from the 2011 Income Statements of three nationwide carriers (Verizon, AT&T and Sprint). We calculated that these carriers' total costs represent roughly 85 percent of revenues, leaving 15 percent as net cash flow (profit). We also calculated the approximate breakdown of those costs as a share of revenue: amortized capital (15 percent); service (25 percent); equipment (15 percent); and selling, general and administrative (30 percent). A requirement for more cell sites would increase the share of revenue going to amortized capital by the same proportion. In addition, it would increase the share of revenue going to service by about half of that amount, because service costs include network access and transportation costs, both of which are positively related to the number of cell sites operated by a carrier. As a result, the share of carrier revenue devoted to costs would increase, and net cash flow would decrease.

Third, the value of a spectrum license is roughly equal to the net present value of the profits that the licensee can derive from using it.[63] *Thus, a decrease in net cash flow translates into a decrease in the value of the corresponding spectrum that is proportional or greater.*[64] *For the three interference scenarios we have highlighted (5 percent, 20 percent and 35 percent capacity loss), the corresponding (proportional) decrease in spectrum value is: 9 percent, 43 percent and 93 percent. (*Table 2 *presents this information for all seven interference scenarios.)*

Although our estimate of the effect of interference on spectrum value is based on a modeling exercise that uses industry investment data, it is borne out by empirical evidence from two recent auctions. In Auction 73, held in 2008, the FCC auctioned five blocks (A, B, C, D and E) of the 700 MHz band. The lower portion of the A Block sat adjacent to TV Channel 51, whose operation made two-way mobile communications infeasible in the vicinity of the broadcast tower—a limitation that ultimately affected fully 21 percent of the U.S. market. In Auction 66, held in 2006, the FCC auctioned 70 megahertz of spectrum in the AWS-1 bands (1710-1755 and 2110-2155 MHz), none of which sat adjacent to an operating TV channel. The prospect of interference to service in the Lower 700 MHz A Block had the expected effect: the licenses in affected markets sold for significantly less than their AWS-1 counterparts in Auction 66. For

63 Coleman Bazelon and Giulia McHenry, "Spectrum Value," *Telecommunications Policy,* 37 (2013): 737-747.

64 To the extent that the lower cash flows also push out the timing of the profits, the impact of a decrease in net cash flows on spectrum value can be greater than proportional. Thus, the (proportional) estimates of decreased spectrum value that are reported in this paragraph and elsewhere in this report should be seen as conservative.

example, the Lower 700 MHz A Block license in Chicago sold for 109 percent of the band average price whereas the comparable AWS-1 B Block license in Chicago sold for 162 percent above its band averages.

Table 2: Summary of Spectrum Value Loss and Increase in Cell Sites Associated with Seven Interference Levels

Interference	Cell Site Increase		
Level	Difference	Percent Change	Value Loss
[1]	[2]	[3]	[4]
5%	2,079	5%	9%
10%	4,413	11%	19%
15%	7,004	17%	30%
20%	9,941	24%	43%
25%	13,278	32%	57%
30%	17,144	41%	74%
35%	21,537	52%	93%

Column Sources:
[1]-[4]: Table A-2.

VI. Impact of Diminished Spectrum Value on the Incentive Auction

Common sense tells us that a decline of 9 to 93 percent in the market value of some portion of the 600 MHz band will have an adverse impact on the incentive auction. It is not a straightforward exercise to quantify that impact, however, because the auction process is complex and some of the alternative band-plan scenarios (there are 11 in all) will be more adversely affected than others. Below, we trace the process by which the prospect of interference, through its impact on the value of the 600 MHz spectrum, will damage the auction. As in Section V, our goal is pedagogy more than prediction: we want to illustrate the magnitude of the potential impact rather than to estimate with any precision the outcome of the auction.

Our analysis involves four steps. After describing key features of the auction process, we first look at how the auction would play out absent interference from unlicensed operations in the 600 MHz band; this serves as our baseline. The challenge in this step is to come up with values for the key variables that determine the baseline: the price that broadcasters will demand to relinquish the 600 MHz spectrum and the corresponding amount that bidders will pay to acquire it. Rather than estimate these values ourselves, we draw on plausible estimates that industry experts have offered in public statements. Second, we look at how the prospect of interference, through its adverse impact on the value of the spectrum, will affect this baseline. We look at the effect both on the amount of revenue generated and on the sheer quantity of spectrum repurposed from broadcasting to mobile broadband use. Third, we summarize the social welfare impact of these two effects. Finally, having analyzed the direct effects of the interference, we look at the possibility that it could have another, indirect, effect by reducing the number of parties willing to bid in the auction.

A. Background on the Auction Process

The incentive auction is "two-sided." One side is the reverse auction, which will recover spectrum from TV broadcasters who agree to relinquish some or all of their spectrum usage rights in exchange for incentive payments. The other side is the forward auction, which will sell the reclaimed spectrum usage rights to wireless carriers and other bidders. The receipts from the forward auction must, at a minimum, be sufficient both to compensate the broadcasters for their relinquished spectrum rights and to cover two related expenses—the cost of relocating the remaining broadcasters to new channels and the FCC's administrative expenses. (We refer to these costs collectively as "total clearing costs," "required clearing costs" or "clearing costs").

Initially, the FCC also specified that receipts from the forward auction would need to pay for the nationwide public safety network, FirstNet, insofar as the AWS-3 auction did not generate sufficient revenue to cover that cost. That requirement no longer exists, because the AWS-3 auction generated sufficient revenue to cover the entire cost of FirstNet. However, the pre-AWS-3 requirement is relevant to our methodology, discussed below, for estimating what broadcasters will demand as compensation for their spectrum rights.

Some additional detail on the auction is necessary to lay the groundwork for our analysis. The forward auction has two separate stages. In the first stage, known as the allocation stage, participants will bid on ostensibly interchangeable 10-megahertz blocks of paired spectrum (5 megahertz of uplink and 5 megahertz of downlink spectrum).[65] That is, participants will not be able to identify the specific block(s) of spectrum on which they are bidding. In the second stage, known as the assignment round, winners from the allocation stage will bid on specific, identifiable blocks of spectrum of the same size.

Two features of the allocation stage are key to understanding how interference from unlicensed operations will affect the incentive auction. First, the interchangeable nature of the blocks means that bidders will be unable to distinguish between the ones that are subject to interference and the ones that are not. Thus, at the allocation stage, rational bidders will base their bids on a worst-case scenario—that is, they will assume that all blocks are impaired. Although participants will be able to bid up the price of the blocks that are not subject to interference in the assignment round, the prospect of interference will suppress the bidding for all blocks in the allocation stage.[66]

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[65] Technically speaking, some blocks may not be interchangeable, but for reasons that do not affect our analysis. To elaborate, the FCC's proposed auction rules provide for a second type of generic spectrum license; it would be used only in the event that those TV stations that continue to operate cause significant "impairment" in bands licensed for mobile broadband (if this happens, it would likely be limited to a few dense urban areas such as New York City). Although bidders could distinguish between these impaired licenses and the other 600 MHz licenses at the allocation stage, the two types of licenses would be equally vulnerable to interference from unlicensed operations in the guard bands. Thus, we ignore this technicality in our analysis.

[66] Two points are key to the calculation of allocation-stage revenues, and both require some explanation. First, as noted above, rational bidders will base their allocation-stage bids on a worst-case assumption that *all* blocks are subject to interference. The alternative strategy is for bidders to base their allocation-stage bids on the *probability* that a given block is subject to interference. That strategy would in fact be rational if, in the subsequent assignment round, the blocks subject to interference were going to be randomly assigned to bidders. But given the fact that the blocks will be identifiable

Continued on next page

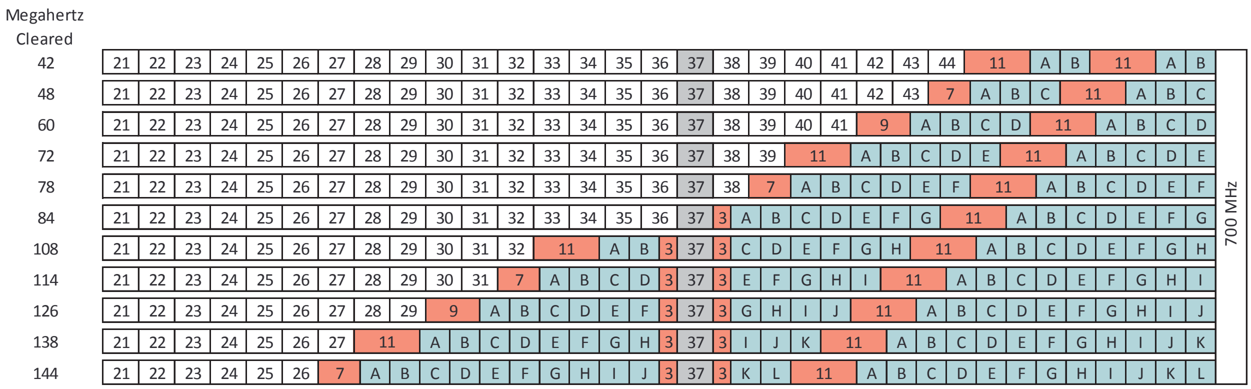
Second, even though some of the revenue lost at the allocation stage due to the prospect of interference will be recouped in the assignment round, the amount of TV spectrum that gets cleared depends solely on the revenue generated at the allocation stage. To elaborate, the requirement that forward-auction receipts cover the clearing costs is, in fact, a requirement on allocation-stage receipts. As a result, the prospect of interference, by reducing the revenue generated at the allocation stage of the forward auction, will limit how much spectrum even makes it to the assignment round.

The FCC has developed a band plan for the 600 MHz band that contains eleven alternate scenarios, as shown in Figure 1. The scenarios vary based on the number of television channels that get cleared in the reverse auction (ranging from 7 to 24 channels) and the corresponding number of paired, 10-megahertz bands that get sold in the forward auction (ranging from 2 to 12 bands). For example, if the FCC clears 84 megahertz of TV broadcast spectrum, it will sell seven paired, 10-megahertz bands (a total of 70 megahertz) in the forward auction and reallocate 14 megahertz of spectrum as guard bands (the 11-megahertz duplex gap plus a three-megahertz guard band). To take another example, if the FCC clears 126 megahertz of broadcast spectrum, it will sell ten paired bands (a total of 100 megahertz) and reallocate 26 megahertz as guard bands (the 11-megahertz duplex gap plus a nine-megahertz guard band and two three-megahertz guard bands).

Continued from previous page

in the assignment round—i.e., bidders will be able to distinguish between the blocks that are subject to interference and the blocks that are not—at the allocation stage, rational bidders will assume the worst (all blocks are subject to interference). The intuition here is that bidders have a given amount of money to spend in the incentive auction; given that they will be able to spend it more intelligently in the assignment round, they will opt to withhold some of it at the allocation stage. Second, in the allocation stage, once a bidder places a bid on one of the generic blocks, that bid remains active even if that phase of the allocation stage is unsuccessful (because the revenue is not sufficient to cover the clearing costs) and the FCC proceeds to the next phase (for which the target for the amount of broadcast spectrum to be cleared is smaller). This is relevant because, as we will discuss, some of the FCC's target band plans will be more vulnerable than others to the impact of interference from unlicensed operations. Because bidders will not know which band plan will be the one to prevail, they will formulate their bids based on the assumption that the most impacted band plan will prevail.

Figure 1: FCC's 600 MHz Band Plan



Source: 600 MHz Report and Order, Appendix C, para. 116.

As discussed earlier in this report, the FCC's 600 MHz Report and Order authorized unlicensed devices to use the spectrum in the guard bands (14 megahertz for the 84-megahertz scenario, for example). Each scenario includes an 11-megahertz duplex gap and either one or three additional guard bands, with four possibilities for the size of guard bands: 11 megahertz, nine megahertz, seven megahertz and three megahertz. The amount of spectrum devoted to guard bands ranges from 14 megahertz (in the 84-megahertz scenario) to 28 megahertz (in the 138-megahertz scenario). (In its recent 600 MHz Unlicensed NPRM, the FCC proposes to have a three-megahertz separation between guard band operations and LTE downlink services, which means that the seven-megahertz guard bands would be off limits to unlicensed guard band devices (the NPRM does not affect the three-megahertz guard bands). However, because this is a proposal and not a final rule, we do not incorporate it into our analysis.)

In the auction, the FCC will seek to attain the largest band plan possible for which revenues from the allocation stage are sufficient to pay all of the corresponding clearing costs. If the largest band plan does not raise that level of revenues, the FCC will move to the next largest band plan, and so on. If the smallest band plan does not raise sufficient revenues to cover its clearing costs, the auction will be unsuccessful.

B. Incentive Auction in the Absence of Interference Risk (Baseline)

To establish the baseline for our analysis of the impact of interference from unlicensed operations in the 600 MHz guard bands, we consider how the incentive auction might play out in the absence of any risk of interference. We look first at potential receipts from the forward auction and then at potential payments (clearing costs) in the reverse auction.

1. Forward Auction Receipts

The price that bidders will pay for the 600 MHz spectrum will reflect the overall demand for spectrum at the time of the auction, which in turn will depend on the anticipated growth of wireless based services, the expected supply of spectrum and other factors. It is difficult to estimate that price with any precision given that the auction is months away and some of the rules have not yet been set. However, we can develop a rough estimate.

Prior to the AWS-3 auction, there was a "working hypothesis" in the spectrum community that the 600 MHz spectrum would have an auction value of around $1.50/MHz-pop. A public declaration by a senior executive of AT&T in May 2014 said that a threshold price of $1.50/MHz-pop "will attract significant broadcaster interest."[67] Greenhill and Co., a firm retained by the FCC, used that same estimate in an information package on the incentive auction that it prepared for broadcasters in October 2014.[68]

The results of the FCC's recent AWS-3 auction, in which paired spectrum sold for an average price of $2.71/MHz-pop,[69] clearly require an upward revision to the "working hypothesis" estimate of the value of the 600 MHz spectrum. However, it is unlikely that the 600 MHz spectrum will attract similarly high bids for several reasons.

One reason is timing: the carriers will be able to access the AWS-3 spectrum several years before the 600 MHz band spectrum is available. To elaborate, some portions of the AWS-3 uplink spectrum are encumbered by federal users that are not required to clear it for at least several years. However, the more valuable AWS-3 spectrum, namely the portions to be used for

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67 "We believe that a threshold price of $1.50 MHz-pop will attract significant broadcaster interest, as it should, so that an initial clearing target of 70 MHz or more is very likely." Jim Cicconi, "AT&T Statement on FCC's Spectrum Aggregation and Auction Eligibility Order," *AT&T Public Policy Blog*, May 15, 2014; available at http://www.attpublicpolicy.com/fcc/att-statement-on-spectrum-aggregation-and-auction-eligibility-order/.

68 Greenhill and Co., "Incentive Auction Opportunities for Broadcasters," PowerPoint Presentation, October 2014; available at http://wireless.fcc.gov/incentiveauctions/learn-program/docs/ia-opportunities-book.pdf.

69 Phil Goldstein, "AWS-3 Auction Results: AT&T Leads with $18.2B, Verizon at $10.4B, Dish at $10B, and T-Mobile at $1.8B," *Fierce Wireless*, January 30, 2015; available at http://www.fiercewireless.com/story/aws-3-auction-results-att-leads-182b-verizon-104b-dish-10b-and-t-mobile-18b/2015-01-30.

downlink, will be available immediately.[70] Moreover, AWS-3 licensees may be able to accelerate the clearing schedule for that spectrum, as occurred following the FCC's auction of Personal Communications Service spectrum in the mid-1990s. By contrast, assuming that the incentive auction is successfully completed in 2016, it will take more than three years for any of the broadcast spectrum to be cleared.[71] Moreover, there will be little opportunity for licensees to influence that schedule.

A delay (or gain) of a few years could have a meaningful impact on spectrum value. Using a 15 percent discount rate (a plausible estimate of the cost of capital for a marginal bidder), a two-year delay in the availability of spectrum would (all else equal) reduce the value of the spectrum by approximately one quarter. A similar reduction in spectrum value would result if one substituted a 10 percent discount rate and assumed a three-year delay in the availability of the spectrum.[72]

A second reason the 600 MHz spectrum is unlikely to attract similarly high bids is its location. The AWS-3 spectrum that was sold occupies higher frequencies: 1695-1710, 1755-1780 and 2155-2180 MHz. For the reasons discussed in Sections II and III of this report (and contrary to popular perception), higher frequencies may be preferable because they provide greater capacity (as opposed to coverage) though the use of MIMO.

A third reason that the 600 MHz spectrum may fetch lower prices than the AWS-3 spectrum has to do with the role played by Dish Network Corp. According to some participants, the presence

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70 AT&T recently stated that it expects initially to use the additional AWS-3 spectrum for supplemental downlink. See AT&T Inc., "AT&T Adds High-Quality Spectrum to Support Customers' Growing Demand for Mobile Video and High-Speed Internet," *AT&T Newsroom*, January 30, 2015; available at http://about.att.com/story/att_adds_high_quality_spectrum_to_support_growing_demand_for_mobile_video_and_high_speed_internet.html.

71 Broadcast TV stations that are successful in the reverse auction will have up to 39 months to move once the forward auction concludes. FCC, "Broadcast Incentive Auction 101," PowerPoint Presentation, June 25, 26 & 27, 2014, available at http://wireless.fcc.gov/incentiveauctions/learn-program/Broadcast_Incentive_Auction_101_slides.pdf.

72 Coleman Bazelon and Giulia McHenry, "Staying on Track: Realizing the Benefits from the FCC's Incentive Auction without Delay," Attachment 1 in Comments of LocusPoint Networks, LLC, by William D. deKay and Ravi Potharlanka, *Broadcast Incentive Auction Comment Public Notice Auction 1000, 1001 and 1002* and *Expanding the Economic and Innovation Opportunities of Spectrum Through Incentive Auctions*, AU Docket No. 14-252 and GN Docket No. 12-268 (February 20, 2015).

of Dish and the two designated entities it worked through served to drive the prices of the AWS-3 spectrum higher than they otherwise would have been. [73]

Based on these factors, we posit $2.00/MHz-pop as our probable value of 600 MHz band spectrum. This represents an increase of one-third in the earlier "working hypothesis" valuation of the 600 MHz spectrum ($1.50/MHz-pop) and a decrease of one-quarter in the AWS-3 valuation ($2.71/MHz-pop). Were we to use a higher valuation in the analysis that follows, it would "soften" our quantitative results somewhat but it would not alter our qualitative conclusions.

To illustrate how we calculate forward auction receipts, consider the 84-megahertz scenario. Under that scenario, the forward auction would sell the rights to 22.1 billion MHz-pops of spectrum. This figure is the product of the U.S. population (308,745,538[74]) times the amount of spectrum to be auctioned off for mobile broadband under this target scenario (70 megahertz). Based on the spectrum valuation posited above ($2.00/MHz-pop), receipts from the forward auction would total about $44.3 billion.

Table 3 (Column 4) shows the corresponding level of forward auction receipts for the ten other band-plan scenarios. For example, under the worst-case scenario, in which 42 megahertz of broadcast spectrum get cleared and 20 megahertz are repurposed for broadband wireless, the auction would raise only about $12.6 billion. Under the best-case scenario, in which 144 megahertz get cleared and 120 megahertz are repurposed for broadband wireless, the auction would raise more than $75 billion.[75]

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73 Joan Marsh, "Lessons from Auction 97 for Future Auctions," *AT&T Public Policy Blog*, February 20, 2015, http://www.attpublicpolicy.com/.

74 Census Bureau, "County Totals Dataset: Population, Population Change and Estimated Components of Population Change: April 1, 2010 to July 1, 2013," accessed September 10, 2014; available at http://www.census.gov/popest/data/counties/totals/2013/CO-EST2013-alldata.html.

75 In theory, the prospect of an increase in the supply of spectrum will itself reduce what bidders are willing to pay for that spectrum in an auction. (Economists call this the "price elasticity of supply.") By this logic, the price of a unit of 600 MHz spectrum is not constant: it will be slightly lower under the FCC's larger band-plan scenarios than under the smaller ones. However, this effect will be small and thus we ignore it.

2. Reverse Auction Payments

To calculate our baseline (auction without the risk of interference from unlicensed operations), we must also have a rough estimate of what broadcasters will demand as compensation for their spectrum rights. We rely on plausible public statements to get an estimate of this value. One such statement comes from the law firm Skadden, Arps, Slate, Meagher & Flom LLP, which estimated in June 2014 that the FCC would raise between $20 billion and $25 billion from wireless carriers.[76] We also rely on a statement by an AT&T executive who around the same time speculated that the FCC would need to raise $30 billion in order for the incentive auction to work.[77]

These statements appear to represent the experts' judgment at the time as to the total amount of money the FCC would need to receive both to compensate broadcasters and to cover the non-compensation clearing costs: broadcaster relocation costs, FCC administrative expenses, and the cost of FirstNet insofar as the revenues from the AWS-3 auction fell short. The non-compensation clearing costs were reasonably well understood at the time our experts made their estimates: $7 billion for FirstNet and $1.75 billion for broadcaster relocation and FCC administrative costs.[78] Thus, we back that amount ($8.75 billion) out of our experts' estimates (note that by using the total cost of FirstNet, we are being conservative), and we treat the balance as their implicit estimates of what it would take to compensate broadcasters. These implicit estimates range from $11.25 billion ($20 billion minus $8.75 billion) to $21.25 billion ($30 billion minus $8.75 billion).

The experts did not indicate which of the FCC band-plan scenarios they had in mind when they made their estimates. However, the popular expectation at the time was that the FCC would clear between 60 megahertz and 84 megahertz of broadcast spectrum. Thus, for purposes of our analysis, we will assume that the low-end expert estimate ($20 billion) corresponds to the 60-

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76 Ivan A. Schlager, John M. Beahn, Joshua A. Gruenspecht, and David H. Pawlik, "FCC Issues Rules for First-Ever Incentive Auction of TV Broadcast Spectrum," *Skadden, Arps, Slate, Meagher & Flom LLP,* June 13, 2014; available at http://www.skadden.com/insights/fcc-issues-rules-first-ever-incentive-auction-tv-broadcast-spectrum.

77 Ted Johnson, "FCC Approves Plan to Auction Off Broadcast Airwaves for Wireless Use," *Variety,* May 15, 2014.

78 *Ibid.*

megahertz scenario and the high-end expert estimate ($30 billion) corresponds to the 84-megahertz scenario.

Using our two implicit estimates of broadcaster compensation costs ($11.25 billion for 60 megahertz and $21.25 billion for 84 megahertz), we calculate the compensation costs for all 11 of the FCC's band-plan scenarios. Broadcaster compensation payments are expected to increase nonlinearly, because the more spectrum the FCC clears, the higher the price it will have to pay to all of the broadcasters it buys out. However, to simplify the analysis and avoid overestimating broadcaster compensation costs, we assume that the relationship is linear.[79]

One adjustment is necessary based on the results of the AWS-3 auction. Our experts' estimates of the FCC's total revenue requirement (i.e., total clearing costs)—and their implicit estimate of what broadcasters would demand as compensation—reflected their expectation at the time of forward auction receipts. That expectation in turn would have reflected the "working hypothesis" that the 600 MHz spectrum was worth $1.50/MHz-pop. In light of the higher expected value for the 600 MHz spectrum, it likely will cost more to compensate broadcasters; that is so, both because the FCC can afford to be more generous to broadcasters and because doing so will encourage additional broadcaster participation.[80] Having increased our valuation of the 600 MHz spectrum by one-third (from $1.50/MHz-pop to $2.00/MHz-pop), as explained earlier, we increase the range of estimated total clearing costs by one-third as well.

In Column 5 of Table 3, we show the total clearing costs for all FCC band-plan scenarios; this amount includes broadcaster compensation costs plus the non-compensation clearing costs. We exclude the cost of FirstNet here, which means that the non-compensation clearing costs are $1.75 billion. (Although in the calculation described above, we assumed that our experts' estimates included the cost of FirstNet, it makes sense to exclude that cost here, because the incentive auction will no longer need to cover it.)

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79 Based on the assumption of a linear relationship, we fit a line between our two data points: 60 megahertz, $11.25 billion and 84 megahertz, $21.25 billion. The resulting mathematical relationship, which we use to derive broadcaster compensation costs for the other nine scenarios, is: broadcaster compensation costs (in billions) = -13.75 + repurposed spectrum (MHz) × 0.42.

80 Although the actual payments to broadcasters will be determined through the play of the auction, the FCC can influence the payment level in the way that it crafts the relevant rules. The FCC wants to encourage broadcaster participation, and making the expected payments to broadcasters more generous is one way to do so.

The total clearing costs range from $6.8 billion for our worst-case band-plan scenario (42 megahertz) to $75.9 billion for our best-case band-plan scenario (144 megahertz). For the (formerly) "popular expectation" scenarios—60 megahertz and 84 megahertz—the total clearing costs are $16.8 billion and $30.1 billion, respectively. For two of the more ambitious band-plan scenarios—126 megahertz and 138 megahertz—the total clearing costs are $53.4 billion and $60.1 billion. (In light of the higher-than-expected revenues from the AWS-3 auction, popular expectations may be shifting to FCC band plans that clear larger amounts of spectrum.)

Table 3: Summary of Estimated Forward Auction Receipts, Clearing Costs, and Incentive Auction Outcome

				$2.00/MHz-pop		
MHz Repurposed	Available MHz	Assumed MHz-Pop Value	Value of Forward Auction with no Interference	Clearing Costs	Min. Interference needed for Forward Auction Receipts to Fall Below Clearing Costs	Value of Forward Auction with Min. Interference
[1]	[2]	[3]	[4]	[5]	[6]	[7]
42	20	$2.00	$12.6	$6.8	25%	$5.4
48	30	$2.00	$19.0	$10.1	25%	$8.1
60	40	$2.00	$25.3	$16.8	20%	$14.4
72	50	$2.00	$31.6	$23.4	15%	$22.0
78	60	$2.00	$37.9	$26.8	15%	$26.4
84	70	$2.00	$44.3	$30.1	20%	$25.2
108	80	$2.00	$50.6	$43.4	10%	$40.9
114	90	$2.00	$56.9	$46.8	10%	$46.0
126	100	$2.00	$63.2	$53.4	10%	$51.2
138	110	$2.00	$69.5	$60.1	10%	$56.3
144	120	$2.00	$75.9	$63.4	10%	$61.4

Column Sources:
[1]-[2]: 600 MHz Report and Order.
Notes:
[4]-[5], [7] are reported in billions.
[3]: Assumed price based on statement by AT&T senior executive, Greenhill and Co. estimates and AWS-3 auction results. See Section VI.B.1.
[4]: [2] x $2.00 x 316,128,839.
[5]: Broadcaster payments (estimated from a linear model). Estimated payments are increased by 133 percent and also include $1.75 billion in assumed broadcaster relocation and FCC administrative costs.
[6]: See Table B-1. This is the minimum level of interference from unlicensed operations needed to cause forward auction receipts to fall below clearing costs.
[7]: [4] x (1 - Cash Flow Interference Percentage (see Table A-2, [17])).

C. Incentive Auction with Interference Risk

In the second step of our analysis, we illustrate how the outcome of our baseline auction changes when we take the risk of interference into account. We define a block of spectrum that is subject to interference as any block in which the downlink portion is adjacent to a guard band (including a duplex gap). As Section IV noted (and as the recent Comments of CTIA demonstrate), the interference risk may well extend beyond the adjacent band. But to keep the analysis simple, and to err on the side of being conservative, we assume that it will affect only the bands adjacent to guard bands (including the duplex gap).[81]

1. Allocation Stage

As discussed earlier, at the allocation stage of the forward auction, bidders will be unable to distinguish between those blocks that are subject to interference and those that are not. Thus, rational bidders will treat all blocks as if they were subject to interference. For example, in our illustrative scenario, in which 84 megahertz of spectrum are cleared and 70 megahertz of spectrum (seven 10-megahertz blocks) are repurposed for wireless broadband, bidders will bid on all seven blocks as if they were subject to interference even though only two paired blocks are adjacent to guard bands. Thus, the revenue from the allocation stage will decrease by the full amount that we calculated in Section V, ranging from 9 percent (if interference causes a 5 percent capacity loss) to 93 percent (if it causes a 35 percent capacity loss). (See Column 4 of Table 2.)

Column 4 in Table 3 shows the allocation-stage revenues for each of the 11 band-plan scenarios under conditions of no interference (*i.e.*, our baseline auction conditions). Table B-1 in Appendix B shows the contrasting allocation-stage revenues for the 11 band plans under each of seven interference scenarios. To return to our illustrative scenario (84 megahertz cleared, 70 megahertz sold), with a 5 percent level of interference and a corresponding 9 percent reduction in revenues, allocation-stage revenues will decrease by $4 billion, to about $40.3 billion (Columns 5 and 6). With a 20 percent level of interference and the corresponding 43 percent reduction in revenues, allocation-stage revenues will decrease by about $19 billion, to $25.2 billion (Columns 5 and 9). Finally, with a 35 percent level of interference and the corresponding

81 We make two additional assumptions regarding interference from unlicensed operations. One, we assume that unlicensed operations will occur in the three-megahertz guard bands adjacent to Channel 37; thus, the bands adjacent to those guard bands will be affected by interference. This assumption is consistent with the FCC's 600 MHz Report and Order, which outlines the use of unlicensed devices in all of the guard bands. See 600 MHz Report and Order, paras. 677-688. Two, in cases in which interference affects only the downlink block in a paired block, we assume that the value of the entire paired block will be reduced since the auction is limited to paired spectrum.

93 percent reduction in revenues, allocation-stage revenues will decrease by about $41.2 billion, to $3 billion (Columns 5 and 12).

2. Impact of Reduced Allocation-Stage Revenues on the Amount of Spectrum Cleared

As discussed earlier, the quantity of broadcast spectrum that gets cleared in the auction will depend solely on the revenues generated at the allocation stage. (If the allocation-stage revenues for a given band-plan scenario do not cover the total clearing costs, the FCC will ratchet down to the next largest band plan.) Thus, even though some of the revenues lost at the allocation stage due to interference will get recouped in the assignment round, it will make no difference in terms of the amount of cleared spectrum. Herein lies the biggest source of damage to the incentive auction from the FCC proposal to allow unlicensed operations in the 600 MHz guard bands.

To illustrate the enormously detrimental impact that the FCC's proposed policy could have, we show the minimum amount of interference impact that it would take to cause allocation-stage revenues to fall below the required clearing costs. Column 6 in Table 3 displays this information for each of the 11 band-plan scenarios. At the 10 percent level of interference, the allocation-stage revenues would fail to cover the required clearing costs for the FCC's five largest band plans. Under this scenario, the best possible outcome of the auction would be the illustrative band plan, in which 70 megahertz would get repurposed—50 megahertz less than under the largest band plan. At the 15 percent level of interference, allocation-stage revenues would cover clearing costs only for the three smallest band plans—the ones that repurpose 40 megahertz or less—and for the illustrative band plan. (The illustrative band plan can "tolerate" more interference than some of the smaller band plans because it has less spectrum devoted to guard bands.) At the 20 percent level of interference, only two of the 11 band plans (the ones that would repurpose 30 megahertz or less) would cover their clearing costs.

3. Assignment Round

In the assignment round of the incentive auction, bidders will be able to distinguish between those blocks of spectrum that are subject to interference and those that are not. Thus, the assignment round should generate considerable additional revenues—revenues that bidders withhold in the allocation stage to ensure that, in the assignment round, they can afford to buy the blocks not subject to interference. We do not try to estimate the assignment-round revenue, however, because it will not affect the amount of spectrum that gets cleared. Nor do we try to estimate the amount of assignment-round revenue that would be foregone due to interference.

D. Welfare Effects

The risk of interference from unlicensed operations in the 600 MHz guard bands could entail an enormous social cost—well beyond the foregone assignment-round revenue—if it causes any reduction in the amount of TV spectrum that gets repurposed for broadband wireless. We estimate that every 10 megahertz of broadcast spectrum that does not get repurposed represents at least a $60 billion loss in consumer welfare.[82] The analysis above shows that it would take as little as 10 percent interference impact to cause a 50-megahertz reduction in the maximum amount of spectrum repurposed for wireless broadband. That scenario would represent a loss in consumer welfare of more than $300 billion.

E. Feedback Loops and the Potential for an Unsuccessful Auction

In addition to these direct effects, the prospect of interference from unlicensed operations in the 600 MHz guard bands may have an indirect effect on the auction by reducing the number of bidders, which in turn will reduce the amount of auction revenue. The key insight here is that some LTE providers will be able to deal with the risk of interference better than others.

To elaborate (and as discussed in Section V), to work around the effects of interference from unlicensed operations in the 600 MHz band, a provider needs spectrum that is not subject to interference which it can substitute for the spectrum that is subject to interference. For example, a provider could compensate for the risk of interference in a 10-megahertz channel by adding

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82 Producer surplus = 10 megahertz × $2.00/MHz-pop × 316 million pops ≈ $6 billion. Economists estimate that, in the case of spectrum, the consumer welfare is at least 10 times the value of the producer surplus, or $60 billion in this example. See Gregory L. Rosston, "The Long and Winding Road: The FCC Paves the Path with Good Intentions," *Telecommunications Policy* 27 (2003): p. 513. More generally, economists have shown that the ratio of consumer welfare to producer surplus ranges from 10-to-1 to 20-to-1. When discount rates are low, as they are in the current economic environment, the ratio will be closer to 20-to-1. Thus, our use of a 10-to-1 ratio in this report is conservative. See Coleman Bazelon and Giulia McHenry, "Staying on Track: Realizing the Benefits from the FCC's Incentive Auction without Delay," Attachment 1 in Comments of LocusPoint Networks, LLC, by William D. deKay and Ravi Potharlanka, *Broadcast Incentive Auction Comment Public Notice Auction 1000, 1001 and 1002* and *Expanding the Economic and Innovation Opportunities of Spectrum Through Incentive Auctions*, AU Docket No. 14-252 and GN Docket No. 12-268 (February 20, 2015).

cell sites that expand the capacity of alternative, unaffected channels in its network. The more substitutable spectrum it controls, the more easily a provider can work around the effects of interference.

Interference would impose a higher cost on small providers and new entrants because they lack the inventory of substitutable, clear spectrum that incumbent LTE providers have. As a result, small providers and new entrants are less likely to bid on spectrum that is potentially at risk of interference. Even if many of the small providers and new entrants do not ultimately succeed as bidders, their participation in the incentive auction will increase demand and drive prices to higher levels, helping ensure allocative efficiency. Conversely, in their absence, the lack of competition will keep prices artificially low, leading to allocative inefficiency.

This scenario, combined with other unexpected developments, could conceivably result in a situation in which none of the band plans raises sufficient revenues to cover its corresponding clearing costs—i.e., the auction is unsuccessful. If that were to happen, the loss to consumer welfare could be $720 billion or higher ($60 billion times 12 10-megahertz blocks of spectrum in the largest band plan).

Appendix A: Impact of Interference on the Market Value of Spectrum

To estimate the impact of a loss of network capacity on the market value of licensed spectrum in the 600 MHz band, as summarized in Section V of this report, we make two sets of calculations: (1) the number of cell sites that a licensed carrier would need to add to compensate for a loss of capacity, and (2) the impact of that increased capital requirement on the licensee's net cash flow. (We assume that any decline in net cash flow would result in a proportional decline in the value of the spectrum.) We posit that interference from unlicensed operations in the guard bands (including the duplex gap) could reduce capacity in the adjacent blocks of spectrum by anywhere from 5 percent to 35 percent, depending on the severity of the interference; and we estimate the resulting loss in spectrum value for seven discrete interference levels (representing the 5 to 35 percent range in increments of five percentage points). Below, we explain the basis for our calculations.

A. Requirement for Additional Cell Sites

If interference causes a loss of capacity in the existing network, a licensed carrier will need to deploy additional cell sites in order to compensate—that is, to maintain the same level of service to the same number of people. We distinguish between two types of cell sites: "coverage" cell sites, which provide basic geographic coverage, and "capacity" cell sites, which supplement the coverage sites in higher population areas (the denser the population in a given region, the more capacity sites it will require).

To estimate the number of additional cell sites required for a network operating at 600 MHz that experiences interference, we use as a starting proxy the Verizon network which operates using 22 megahertz in the Upper 700 MHz C Block. We know from publicly available information that Verizon has 41,500 cell sites in that network and that it reaches 97 percent of the U.S. population.[83] Using data on U.S. population by county,[84] and based on the assumption that a cell

[83] According to Citi Research Equities, Verizon's Upper 700 MHz C Block had 41,500 LTE cell sites at the end of the third quarter in 2013. See Michael Rollins, Jason Bazinet and Kevin Toomey, "Third Pipe: Next Gen Wireless," Citi Research Equities, June 5, 2014, p. 17. In addition, in its 2013 10-K, Verizon Wireless reports that its Upper 700 MHz C Block spectrum, which the carrier uses to operate its 4G LTE network, covers 97 percent of the U.S. population, or roughly 305 million people. See also Verizon Communications Inc. Form 10-K for the year ending December 31, 2013, p. 2.

site in the 700 MHz band has a coverage radius of 10 miles,[85] we are able to calculate that it takes 7,087 cell sites to achieve geographic coverage of the most densely populated counties whose combined population equals 97 percent of the total U.S. population (2,262 counties in all). Based on that calculation, we assume that, of Verizon's 41,500 cell sites, 7,087 are coverage cell sites and the remaining 34,313 are capacity cell sites. Having determined the breakdown between coverage and capacity cell sites, we are then able to calculate that each cell site in Verizon's network serves a maximum of 7,629 people.[86]

Next, we adjust for differences between Verizon's 700 MHz system and a comparable system operating at 600 MHz. The principal difference is propagation: all else equal, the signal from a cell site operating at 600 MHz will get a slightly better range than one operating at 700 MHz.[87]

Continued from previous page

84 We use 2010 U.S. Census data population projections for 2013. Census Bureau, "County Totals Dataset: Population, Population Change and Estimated Components of Population Change: April 1, 2010 to July 1, 2013," accessed September 10, 2014; available at http://www.census.gov/popest/data/counties/totals/2013/CO-EST2013-alldata.html.

85 The basis for this assumption (10-mile coverage radius) is as follows. We know from public sources cited below that the propagation range for a wireless network that operates at 1900 MHz is three to five miles. We also know from the same sources that the propagation range of a wireless network that operates at 700 MHz is roughly 170 percent greater than one that operates at 1900 MH. Thus, we calculate that the propagation range of a 700 MHz network is eight to 13 miles ($2.7 \times 3 = 8.1$ and $2.7 \times 5 = 13.4$), and we take the rounded average of those two figures to get 10 miles. See Frank Deible, "Understanding Cell Spacing: Differences in Frequency Coverage and Other Factors," Crown Castle, PowerPoint Presentation, slide 2, available at http://www.comptroller.tn.gov/sap/pdf/20131105PresentationUnderstandingCellSpacing.pdf; Tony Melone, "Wells Fargo Securities: Technology, Media & Telecom Conference," Verizon, PowerPoint Presentation, November 10, 2010, slide 13. For simulation purposes, we prevent cell sites from overlapping by assuming that each site covers an area that is the shape of a regular hexagon as opposed to a circle. The "radius" of the hexagon is the distance from the center to any one of the six vertices.

86 We measure capacity in terms of population, instead of subscribers. To calculate the population per cell site in the Verizon network, we use a trial and error method. First, we make an initial "guess" about the population capacity per cell site. Then, by county, we determine how many cell sites are needed to cover the actual population of the county ("population" sites). Next, we subtract the number of coverage sites from the number of population sites for each county, leaving us with the number of capacity sites (if the number is negative, we adjust it to 0). Finally, we sum the number of capacity sites and coverage sites in each county. If this number is greater than the 41,500 sites in Verizon's network, we increase our "guess" of the number of people per cell site and start the process over. Conversely, if this number is less than 41,500, we decrease our "guess." We continue this process until our calibration of total required sites equals 41,500.

87 A second difference between the two networks has to do with spectrum quantity: whereas Verizon's 700 MHz system uses 22 megahertz of spectrum, a 600 MHz system will likely use 20 megahertz. (As

Continued on next page

We assume that a 600 MHz system cell site can serve the same number of people as Verizon's 700 MHz system (a maximum of 7,629). We estimate that a 600 MHz cell site will have a coverage area that is 9 percent greater than that of a 700 MHz cell site. With that larger coverage area (283 square miles versus 260 square miles for a 700 MHz cell site), a non-impacted system operating at 600 MHz will need 59 fewer cell sites than the Verizon 700 MHz system, or 41,441 cell sites in all. Of those, 6,604 will be coverage cell sites and 34,837 will be capacity cell sites.[88]

Finally, we calculate the impact on that hypothetical 600 MHz system of a decrease in network capacity. We treat a loss of capacity as equivalent to a decrease in the maximum number of people who can be served per cell site. Thus, with a 5 percent loss of capacity, the 600 MHz system can serve a maximum of 7,247 people per cell site (95 percent of the 7,629 people served per cell site in our baseline calculation). That change does not alter the number of coverage sites needed, but it does increase the number of capacity sites needed by 2,079, for a total of 36,916. Thus, the total number of cell sites needed for a system impacted at the 5 percent level is 43,520 (6,604 plus 36,916), which is 5 percent more than the number needed by the non-impacted system (41,441).

We perform similar calculations for all seven interference impact scenarios, as shown in Table A-1, Row 11. As the level of interference increases, the percentage of additional cell sites needed

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Continued from previous page

described in Section VI, the FCC plans to auction the 600 MHz spectrum in 10-megahertz blocks, which licensees could combine to create a 20-megahertz system.) To determine how that difference would affect the number of cell sites needed in a 600 MHz system, we performed a calculation parallel to the one described above that we used to adjust for the difference in propagation range. However, in contrast to the difference in propagation range, the difference in spectrum quantity (20 versus 22 megahertz) had a very small effect on our ultimate calculation (described below) of the effect of varying levels of interference on the number of cell sites needed. Thus, we omitted it from the analysis.

88 The total number of cell sites in a given county is equal to the number of coverage sites plus the number of capacity sites. The increased propagation range for the 600 MHz network unequivocally decreases the number of coverage sites needed in the 600 MHz network relative to the 700 MHz network. But in counties where the number of capacity sites exceeds (or equals) the number of coverage sites, the total number of cell sites needed is unaffected by the increased propagation range. Thus, for these counties, an increase in the number of coverage sites will reduce the number of capacity sites. For counties that only have coverage sites (i.e., they have no capacity sites), the total number of cell sites decreases due to the increased propagation range. That is so because, for these counties, there is a reduction in the number of coverage sites needed and no change in the number of capacity sites needed.

goes up disproportionately. At the extreme (35 percent interference impact), a system would need 52 percent more cell sites.

Table A-1: Increase in Cell Sites under Seven Interference Scenarios

		Interference Level						
		5%	**10%**	**15%**	**20%**	**25%**	**30%**	**35%**
		[a]	[b]	[c]	[d]	[e]	[f]	[g]
	Capacity and Coverage Site Calculation (600 MHz)							
[1]	Sites for Coverage Build with Radius Assumed for 600 MHz	6,604	6,604	6,604	6,604	6,604	6,604	6,604
[2]	Additional Capacity Sites Needed with Input Max Pop for 600 MHz	34,837	34,837	34,837	34,837	34,837	34,837	34,837
[3]	Max Pop per Cell for 600 MHz	7,629	7,629	7,629	7,629	7,629	7,629	7,629
[4]	**Total Number of Cell Sites for 600 MHz**	**41,441**	**41,441**	**41,441**	**41,441**	**41,441**	**41,441**	**41,441**
	Capacity and Coverage Site Calculation (600 MHz) with Interference							
[5]	Sites for Coverage Build with Radius Assumed for 600 MHz	6,604	6,604	6,604	6,604	6,604	6,604	6,604
[6]	Assumed Loss in Network Capacity	5%	10%	15%	20%	25%	30%	35%
[7]	Max Pop per Cell for 600 MHz	7,247	6,866	6,484	6,103	5,721	5,340	4,959
[8]	Additional Capacity Sites Needed with Input Max Pop for 600 MHz	36,916	39,250	41,841	44,778	48,115	51,981	56,374
[9]	**Total Number of Cell Sites**	**43,520**	**45,854**	**48,445**	**51,382**	**54,719**	**58,585**	**62,978**
[10]	Difference in Cell Sites	2,079	4,413	7,004	9,941	13,278	17,144	21,537
[11]	**Percentage Increase in Cell Sites**	**5%**	**11%**	**17%**	**24%**	**32%**	**41%**	**52%**

Row Notes:

[1]-[3]: Calculations by The Brattle Group.

[4]: [1] + [2].

[5]: [1].

[6]: Assumed loss in network capacity.

[7]: [3] x (1 - [6]).

[8]: Sum of cell sites needed for first 2,262 counties.

[9]: [5] + [8].

[10]: [9] - [4].

[11]: [10] / [4].

B. IMPACT ON NET CASH FLOW

An increase in the requirement for cell sites will adversely affect a carrier's net cash flow. To calculate the impact on a carrier's operating system at 600 MHz, we derived cost information from the 2011 Income Statements of three nationwide wireless carriers (Verizon, AT&T and Sprint). We calculated that the carriers' total costs represent 85 percent of revenues, leaving 15 percent as net cash flow (profit). We also calculated the breakdown of those costs as a share of revenue: amortized capital (15 percent); service (25 percent); equipment (15 percent); and selling, general and administrative (30 percent).

A requirement for more cell sites will increase the share of carrier revenue going to amortized capital. The vast majority of a carrier's capital expenditures are related to the number of cell sites. Thus, we assumed a proportional increase in that cost item. That is, a 5 percent increase in cell sites will increase the share of revenue going to amortized capital by 5 percent, which represents a 0.75 percentage point increase (5 percent of 15 percent). The increased share of revenue going to amortized capital that results from each of the seven scenarios is shown in Row 11 of Table A-2.

A requirement for additional cell sites will also increase the share of carrier revenue going to service the network. The cost of service includes costs related to network access and transportation, both of which are a function of the number of cell sites that the carrier operates.[89] We used Verizon's historical financial data to estimate the increase in service expenditures that results from an increase in a network's capital expenditures; we find that for every 1 percent increase in capital expenditures, service expenditures increase by roughly 0.5 percent.[90] That is, a 5 percent increase in cell sites will increase the share of revenue going to service expenditures by 2.4 percent, which represents a 0.6 percentage point increase (2.4 percent of 25 percent). The

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89 More specifically, according to Verizon, the cost of service includes "salaries and wages, benefits, materials and supplies, content costs, contracted services, network access and transport costs, wireless equipment costs, customer provisioning costs, computer systems support, costs to support our outsourcing contracts and technical facilities and contributions to the Universal Service Fund." Verizon Communications Inc. Form 10-K for the year ending December 31, 2013, p. 63.

90 We use quarterly financial data from Verizon Communications Inc. (Q12011 to Q32013) to estimate the following simple linear regression (source: Bloomberg): percent change in service expenditures = a + b percent change in capital expenditures. The estimated coefficient for b is 0.48 (10 total observations with an estimated p-value of 0.05), which tells us that for every 1 percent increase in capital expenditures, service expenditures increase by 0.48 percent.

increased share of revenue going to service that results from each of the seven scenarios is shown in Row 12 of Table A-2.

The share of carrier revenue devoted to costs will increase by the sum of the percentage point increases in the share of revenue going to amortized capital and the share of revenue going to service expenditures. With a five percent interference level, the share of revenue devoted to costs will increase from 85 percent to about 86 percent, and net cash flow will decrease from 15 percent to about 14 percent. This represents a 9 percent decline in net cash flow.

Row 17 of Table A-2 shows the percentage decrease in net cash flow that results from each of the seven interference scenarios. In the worst case scenario, with a 35 percent interference level, net cash flow decreases by 93 percent. With an interference level of 20 percent, net cash flow decreases by 43 percent.

Table A-2: Decrease in Net Cash Flow under Seven Interference Scenarios

		Interference Level						
		5%	**10%**	**15%**	**20%**	**25%**	**30%**	**35%**
	Basic Wireless Network Cash Flow Assumptions							
[1]	Cost, amortized capital (% of initial revenue)	15%	15%	15%	15%	15%	15%	15%
[2]	Cost, service (% of initial revenue)	25%	25%	25%	25%	25%	25%	25%
[3]	Cost, equipment (% of initial revenue)	15%	15%	15%	15%	15%	15%	15%
[4]	Cost, SGA (% of initial revenue)	30%	30%	30%	30%	30%	30%	30%
[5]	Total Cost (% of initial revenue)	85%	85%	85%	85%	85%	85%	85%
[6]	Net Cash Flow (% of initial revenue)	15%	15%	15%	15%	15%	15%	15%
	Financial Adjustment							
	Total Number of Cell Sites							
[7]	Without Interference	41,441	41,441	41,441	41,441	41,441	41,441	41,441
[8]	With Interference	43,520	45,854	48,445	51,382	54,719	58,585	62,978
[9]	Change in Cost, amortized capital	5%	11%	17%	24%	32%	41%	52%
[10]	Change in Cost, service	2%	5%	8%	11%	15%	20%	25%
	Implied Adjusted Network Cash Flow							
[11]	Cost, amortized capital (% of initial revenue)	16%	17%	18%	19%	20%	21%	23%
[12]	Cost, service (% of initial revenue)	26%	26%	27%	28%	29%	30%	31%
[13]	Cost, equipment (% of initial revenue)	15%	15%	15%	15%	15%	15%	15%
[14]	Cost, SGA (% of initial revenue)	30%	30%	30%	30%	30%	30%	30%
[15]	Total Cost (% of initial revenue)	86%	88%	90%	91%	94%	96%	99%
[16]	Net Cash Flow (% of initial revenue)	14%	12%	10%	9%	6%	4%	1%
[17]	Discount to Net Cash Flow	9%	19%	30%	43%	57%	74%	93%

Row Sources:
[1]-[6]: Coleman Bazelon and Giulia McHenry, "Spectrum Sharing: Taxonomy and Economics," The Brattle Group, February 6, 2014, Table 3.
[7]-[8]: Network Buildout Model of 600 MHz.
[10]: 0.48 x [9]. This reflects the relationship between capital expenditures and operating expenditures.
Row Notes:
[9]: [8] / [7] - 1.
[11]: (1 + [9]) x [1].
[12]: (1 + [10]) x [2].
[13]: [3].
[14]: [4].
[15]: Sum of [11]-[14].
[16]: 1 - [15].
[17]: ([6] - [16]) / [6].

Appendix B: Value of Spectrum in the Allocation Stage

Table B-1: Value of Spectrum in the Allocation Stage under Seven Interference Scenarios

	MHz Repurposed	Available MHz	Assumed MHz-Pop	Clearing Costs	Interference Level 0%	5%	10%	15%	20%	25%	30%	35%
	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]	[12]
[a]	42	20	$2.00	$6.8	$12.6 **	$11.5 **	$10.2 **	$8.8 **	$7.2 **	$5.4 *	$3.3 *	$0.9 *
[b]	48	30	$2.00	$10.1	$19.0 **	$17.3 **	$15.3 **	$13.2 **	$10.8 **	$8.1 *	$4.9 *	$1.3 *
[c]	60	40	$2.00	$16.8	$25.3 **	$23.0 **	$20.5 **	$17.6 **	$14.4 *	$10.8 *	$6.5 *	$1.7 *
[d]	72	50	$2.00	$23.4	$31.6 **	$28.8 **	$25.6 **	$22.0 *	$18.0 *	$13.5 *	$8.2 *	$2.2 *
[e]	78	60	$2.00	$26.8	$37.9 **	$34.5 **	$30.7 **	$26.4 *	$21.6 *	$16.1 *	$9.8 *	$2.6 *
[f]	84	70	$2.00	$30.1	$44.3 **	$40.3 **	$35.8 **	$30.8 **	$25.2 *	$18.8 *	$11.4 *	$3.0 *
[g]	108	80	$2.00	$43.4	$50.6 **	$46.0 **	$40.9 *	$35.3 *	$28.8 *	$21.5 *	$13.1 *	$3.4 *
[h]	114	90	$2.00	$46.8	$56.9 **	$51.8 **	$46.0 *	$39.7 *	$32.4 *	$24.2 *	$14.7 *	$3.9 *
[i]	126	100	$2.00	$53.4	$63.2 **	$57.5 **	$51.2 *	$44.1 *	$36.0 *	$26.9 *	$16.3 *	$4.3 *
[j]	138	110	$2.00	$60.1	$69.5 **	$63.3 **	$56.3 *	$48.5 *	$39.6 *	$29.6 *	$18.0 *	$4.7 *
[k]	144	120	$2.00	$63.4	$75.9 **	$69.0 **	$61.4 *	$52.9 *	$43.2 *	$32.3 *	$19.6 *	$5.2 *

Column Sources:

[1]-[2]: 600 MHz Report and Order.

[3]: Assumed price based on statement by AT&T senior executive, Greenhill and Co. estimates and AWS-3 auction results. See Section VI.B.1.

[4]: Table 3, Column [5]. Broadcaster payments (estimated from a linear model). Estimated payments are increased by 133 percent and also include $1.75 billion in assumed broadcaster relocation and FCC administrative costs. Reported in billions.

[5]-[12]: Table 3, Column [4] x (1 - Cash Flow Interference Percentage (see Table A-2, [17])). Reported in billions.

Column Notes:

[5]-[12]: Note, * implies clearing costs cover value of spectrum band excluding Interference, and ** implies clearing costs cover value of spectrum band including and excluding Interference.

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